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Diatom biostratigraphy of the Cenozoic glaciomarine Pagodroma Group, northern Prince Charles Mountains, East Antarctica

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Abstract

In the northern Prince Charles Mountains glaciomarine sediments of the Pagodroma Group outcrop on Fisher Massif (Mt Johnston and Fisher Bench Formations) and at the Amery Oasis (Battye Glacier and Bardin Bluffs Formations), at locations 300 and 250 km south of the Amery Ice Shelf edge, respectively. Most of the Pagodroma Group consists of ice-proximal glaciomarine diamict, and a much subordinate (<2%) amount of more ice-distal mudstone. Microfossil biostratigraphy based upon *in situ* and glacially reworked diatoms constrains the ages of the four formations, and identifies at least six intervals of marine fjordal deposition. Sparse diatoms in Mt Johnston Formation diamicts indicate an Early Oligocene age. However, it is unclear whether these diatoms are *in situ* or else are glacially reworked and represent either an immediately prior or more remote past interglacial. The Battye Glacier and Fisher Bench Formations contain *in situ* diatoms and are broadly time equivalent, the former dating between 10.7 and 9.0 Ma and the latter between 12.1 or 10.7 Ma and 8.5 Ma. *In situ* diatoms indicate the Bardin Bluffs Formation to have been deposited between 2.6 and either 1.8 or 0.99 Ma. Glacially reworked diatoms in the Bardin Bluffs and Fisher Bench Formations identify four depositional intervals. The reworked taxa are sourced from Eocene–Oligocene (>30.1 Ma), Middle Miocene (14.5–12.5 Ma and 12.1–11.5 Ma), Early Pliocene (4.9–3.6 Ma) and, tentatively, Late Pliocene (3.4–2.6 Ma) strata. These microfossil data further develop the interpretation that the Pagodroma Group formed during episodes of reduced glacial extent when, in the absence of an ice shelf, marine waters penetrated far southwards into the Lambert Graben of East Antarctica.

Keywords: Antarctic Ice Sheet, Cenozoic, diatoms, Pagodroma Group, Prince Charles Mountains

Introduction

This paper documents siliceous microfossil occurrences in the Cenozoic Pagodroma Group of the northern Prince Charles Mountains (McKelvey *et al*. 2001) in East Antarctica, and assesses the biostratigraphic ages of the strata. The research comprises both new data and some reassessment of previous studies. In addition, diatom assemblage composition, preservation and abundance are used to critically assess the mode of microfossil emplacement. Conceivably the Pagodroma Group microfossils represent (i) *in situ* primary deposition, (ii) aeolian contamination, (iii) glacial or other reworking processes. Understanding the precise mode of microfossil emplacement is crucial to the accurate biostratigraphic age assessment of the Pagodroma Group.

Location and geological setting

The largest single catchment area of the East Antarctic Ice Sheet (~7%) drains through the Lambert Graben (Hambrey & Dowdeswell 1994), which is now covered by the Amery Ice Shelf (Figure 1). This ice shelf grounds along the sides of the graben, and extends nearly 500 km southwestwards from the open sea in Prydz Bay (Phillips *et al*. 1996; Krebs 1997, 1998). The largely ice-free Amery Oasis and the nunatak Fisher Massif, both in the northern Prince Charles Mountains on the western side of the Lambert Graben, are situated ~250 km and ~300 km inland from the seaward edge of the Amery Ice Shelf, respectively (Figure 1). The northern Prince Charles Mountains consist primarily of Proterozoic high-grade metamorphic rocks (Tingey 1991; Mikhalsky *et al*. 2001). However, Permo-Triassic fluvial strata of the Amery Group also occur in the Amery Oasis (Fielding & Webb 1995; McLoughlin & Drinnan 1997).

Appendices 1 and 2 are indicated by an asterisk (*) in the text and are printed at the end of the paper. They are also published as Supplementary Papers, and copies may be obtained from the Geological Society of Australia's website at http://www.gsa.org.au or from the National Library of Australia's Pandora archive at http://nla.gov.au/nla.arc-25194 .

Cenozoic glaciomarine strata of the Pagodroma Group extensively cover the Amery Oasis and Fisher Massif, and outcrop in cliff sections of up to 300 m, with a composite record totaling more than 800 m in thickness in the northern Prince Charles Mountains (McKelvey *et al*. 2001). The Pagodroma Group comprises at least four geographically separated formations: the Mt Johnston and Fisher Bench Formations occur on Fisher Massif, and the Battye Glacier and Bardin Bluffs Formations are distributed about the Radok Lake – Beaver Lake region of the Amery Oasis (Figures 2, 3) (Hambrey & McKelvey 2000a; McKelvey *et al*. 2001; Whitehead & McKelvey 2001). These Cenozoic strata consist of massive and stratified diamict, boulder gravel, and minor laminated sandstone and mudstone, and are interpreted as fjordal deposits that accumulated seawards of tidewater glacier fronts in environments akin to the modern fjords of East Greenland (Hambrey & McKelvey 2000a, b). Each formation was deposited in the Lambert Graben during a phase of glacial recession and marine incursion. Subsequent glacial advances largely eroded the formations (and the underlying basement), and redeposited the sediments on the continental shelf and slope of Prydz Bay (Barron *et al*. 1991; Barker *et al*. 1998; O'Brien *et al*. 2001). The Pagodroma Group outcrops are erosional remnants that now occupy the floors and abut the walls of uplifted former Lambert Graben fjords (Figure 4). Because of this uplift the older Pagodroma Group formations occupy the higher elevations (McKelvey *et al*. 2001; Hambrey & McKelvey 2000a Table 1). Given the known rates of modern east Greenland fjordal sedimentation, it is apparent that the individual formations represent time intervals in the order of only hundreds or thousands of years (Dowdeswell *et al*. 1994). That this stratigraphic record spans an interval of perhaps 35 million years emphasises its extremely fragmentary nature.

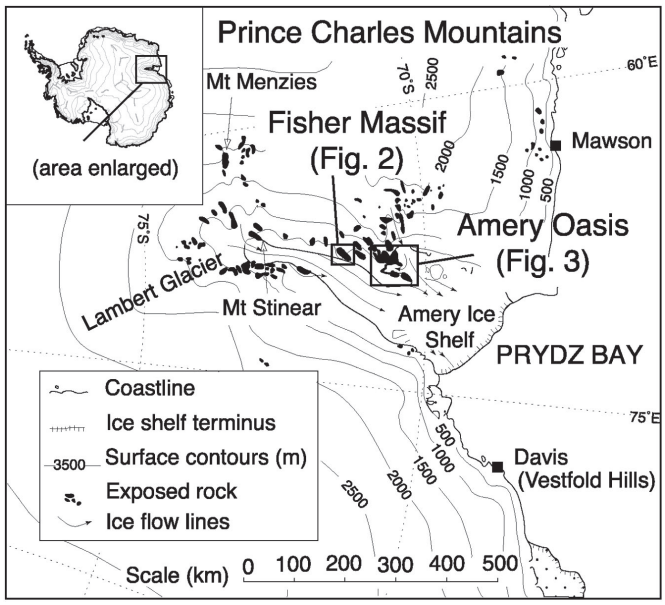

Figure 1. The Prince Charles Mountains showing positions of Fisher Massif and Amery Oasis within the Lambert Glacier – Amery Ice Shelf drainage system. Inset: Location of study area in Antarctica.

Previous work

Cenozoic marine diatoms are known from the Bardin Bluffs Formation (Bardin & Belevich 1985; McKelvey & Stephenson 1990; Whitehead & McKelvey 2001), the Fisher Bench Formation (Laiba & Pushina 1997; McKelvey *et al*. 2001), and the Battye Glacier Formation (Whitehead *et al*. 2003) of the Pagodroma Group. Other microfossils recovered include foraminifers, ebridians, silicoflagellates, sponge spicules and a radiolarian (McKelvey *et al*. 2001; Whitehead *et al*. 2003). Permo-Triassic spores and pollen are also present (Bardin & Belevich 1985). These microfossils have been recovered from the mudstone facies and, to a lesser degree, from the varied diamicts. The most diatom-rich mudstone noted so far, in which biogenic opal comprises up to 12% of the sediment (by dry weight), occurs in the Battye Glacier Formation (Whitehead *et al*. 2003).

Methods

Twenty-seven samples of the Pagodroma Group from Amery Oasis and Fisher Massif were collected by McKelvey, Hambrey and Whitehead during Australian National Antarctic Research Expeditions (ANARE) in 1987/88, 1989/90, 1994 /95, and 1997/98. Additional data reported by Bardin and Belevich (1985), Laiba and Pushina (1997) and Whitehead *et al*. (2003) are also included in the present study. The geographical and stratigraphic positions of the samples are indicated in Figures 2, 3. In Figure 3d only the approximate position of Bardin Bluffs "Top" and "Bottom" samples can be indicated. Sample lithologies are recorded as diamict (Dm) or mudstone (Mud.) (Table 1). More detailed lithological information of sampled intervals exists in Laiba and Pushina (1997), Hambrey and McKelvey (2000a), Whitehead and McKelvey (2001), and Whitehead *et al*. (2003). Samples considered in the latter two publications were collected from >10 cm-deep excavations into outcrops, to avoid possible outcrop surface contamination by airborne diatoms.

Initially strewn microfossil slides were prepared from raw (unprocessed) samples (so indicated in Table 1), mounted with Norland optical adhesive #61 (refractive index = 1.56), and studied with an Olympus BH-2 light microscope at low magnification (×600) and at high magnification (×1000) for taxonomic identification (Figures 5, 6; Appendix 1*). Those raw samples with only sparse or else no apparent diatoms visible were processed further in the University of Nebraska's geological clean laboratory that is dedicated to microfossil extraction from glacial deposits. Here microfossils in these samples were concentrated using elutriation, sieving, gravity-settling and heavy-liquid density separation (using sodium polytungstate), as described in Harwood and Rose (1998). Such samples are recorded as "concentrated" in Table 1, and were studied with a light microscope in the same manner as the "raw" slides.

Quantitative abundance data were collected by systematically scanning microfossil slides. The use of raw and concentrated slides, and the typically fragmented nature of the fossils, precluded the collection of absolute abundance data. Therefore, qualitative indices ranging from 0 to 6 were used

to describe the slide fossil abundances (Table 1): 0, no specimens or fragments observed; 1, at least one specimen or fragment per slide; 2, a few specimens per slide; 3, numerous specimens per slide <10; 4, many specimens per slide >10; 5, a specimen or fragment every few fields of view (×600 magnification); and 6, numerous specimens or fragments on every field of view (×600 magnification). In selected samples the size and abundance of fragments, and the occurrence of whole diatoms and diatomaceous clasts were recorded (Appendix 2*). To further quantify the microfossils, several samples with the highest diatom abundance as seen with the light microscope were analysed for biogenic silica using a SHIMATZU UV1201 spectrophotometer, following the methods of Mortlock and Froelich (1989), at the Antarctic Cooperative Research Centre, Tasmania. This method allows quantification of the siliceous microfossil content as a percentage of the sediment (dry weight) and is referred to as biogenic silica (%opal) (Table 1).

The diatom biostratigraphy of the Pagodroma Group (Figures 7, 8) has been undertaken using established data (Table 2) calibrated to the Berggren *et al*. (1995) geomagnetic polarity time-scale. Descriptive criteria of the microfossil occurrences, assemblage composition and macrofossil association have been tabulated to help assess the mode of fossil emplacement (Table 3).

Results

Siliceous microfossils have been identified in 22 of the 27 samples examined. Diatom abundances vary, but are generally considerably higher in mudstone rather than diamict samples (Table 1). The highest diatom occurrences noted are in raw slides prepared from mudstone samples AM-015 and PCM 98-3Aa-26 of the Fisher Bench and Bardin Bluffs Formations, respectively. Diamict samples yielded only low abundances or else are barren (Table 1). The size and preservation of different fossil elements also varies between samples (Appendix 2*). Extant and extinct planktic and benthic marine, and freshwater taxa have been identified. The assemblages largely consist of planktic marine species, but several samples are rich in benthic marine taxa (e.g. sample PCM 98-3Aa-26 of the Bardin Bluffs Formation).

Mt Johnston Formation

Mt Johnston Formation diamicts (Figures 2, 3) (samples PCM 90-4, PCM 90-5, AM-003, AM-006, and AM-014) contain very sparse extinct planktic marine diatoms and diatom fragments (Table 1), including the species *Coscinodiscus* sp., *Pyxilla* sp., *Stephanopyxis grunowii* Grove & Sturt, *Stephanopyxis splendidus* (Greville) Harwood and *Thalassiothrix*/*Thalassionema* spp.

Fisher Bench Formation

Mudstone and diamict facies of the Fisher Bench Formation (Figures 2, 3) contain marine diatoms and diatom fragments (Table 1). Abundant diatoms occur in mudstone intercalated within diamict at the base of the section (sample AM-015). These diatoms are moderately well-preserved; at least half consist of intact valves, and a very few complete frustules are present. Occasionally the valves are filled with terrigenous mud, similar in appearance to the supporting matrix. During previous studies of sample AM-015 no archive material was retained for biogenic silica analysis; however, a visual estimate of ~2% is suggested through comparison with diatom abundance in the raw slide of sample PCM 98-3Aa-26 from the Bardin Bluffs Formation (Table 1). The AM-015 diatom assemblage consists predominately of planktic marine species, benthic diatoms constituting <1% of the total relative abundance. Much of the assemblage is dominated by the extinct *Actinocyclus ingens* Rattray, and to a lesser degree by the extant taxon, *Coscinodiscus* sp. A, *Coscinodiscus radiatus* Ehrenberg and the extinct *Denticulopsis vulgaris* (Okuno) Yanagisawa & Akiba. Another mudstone, ~66 m above sample AM-015, contains a few planktic diatom fragments of *Thalassiothrix* spp. (sample PCM 90-6). At approximately the same horizon as sample PCM 90-6, Laiba and Pushina (1997) identified a diatom-rich mudstone (sample 36721-4), which contains a predominantly benthic marine assemblage: *Hyalodiscus obsoletus* Sheshukova, *Rhabdonema* sp. and *Rhaphoneis* spp. Some rarer planktic taxa such as *Denticulopsis simonsenii* Yanagisawa & Akiba were also identified.

Diamict sample PCM 90-11 (Figure 2c) contains a diatom assemblage that differs bimodally in preservation and composition (Appendix 2*). The sample yielded an assemblage of well-preserved (intact frustules) benthic diatoms: *Gomphonema angustatum* var. sp. A, *G. angustatum* var. sp. B, *Diploneis* sp. A and *Amphora* sp. A. The remainder of the assemblage consists largely of planktic marine diatom fragments, notably *Chaetoceros* sp. A seta, *Thalassiosira* spp. and rare occurrences of other taxa (Table 1).

Battye Glacier Formation

Diatom occurrences are rare in both the diamict and mudstone facies of the Battye Glacier Formation type section at the Dragons Teeth (samples PCM 90-8 and PCM 90-10B) (Figure 3c Section 1). Fragments of *Thalassiothrix* sp. and a sponge spicule have been recovered (Table 1). However, Whitehead *et al*. (2003) described exceptionally diatom-rich intervals (up to 12% biogenic opal, sediment dry weight) in the Battye Glacier Formation some 13 km to the northeast of the Dragons Teeth, above the western shore of Beaver Lake (Figure 3c Section 2). Here the assemblages in samples PCM 00-116 and PCM 00-118 are rich in benthic diatoms, although planktic taxa such as *D. vulgaris* are present. The Battye Glacier Formation facies at Beaver Lake represent a different (more basinal) glacigene palaeoenvironment to that at Dragons Teeth (Whitehead *et al*. 2003).

Bardin Bluffs Formation

The basal Bardin Bluffs Formation (Figure 3d) consists of two members (Whitehead & McKelvey 2001). The older Member 1, consists largely of mudstone and muddy sandstone, both of which contain abundant dropstones. Member 2, which consists essentially of diamict, disconformably overlies Member 1. Diatoms occur in both members (Table 1).

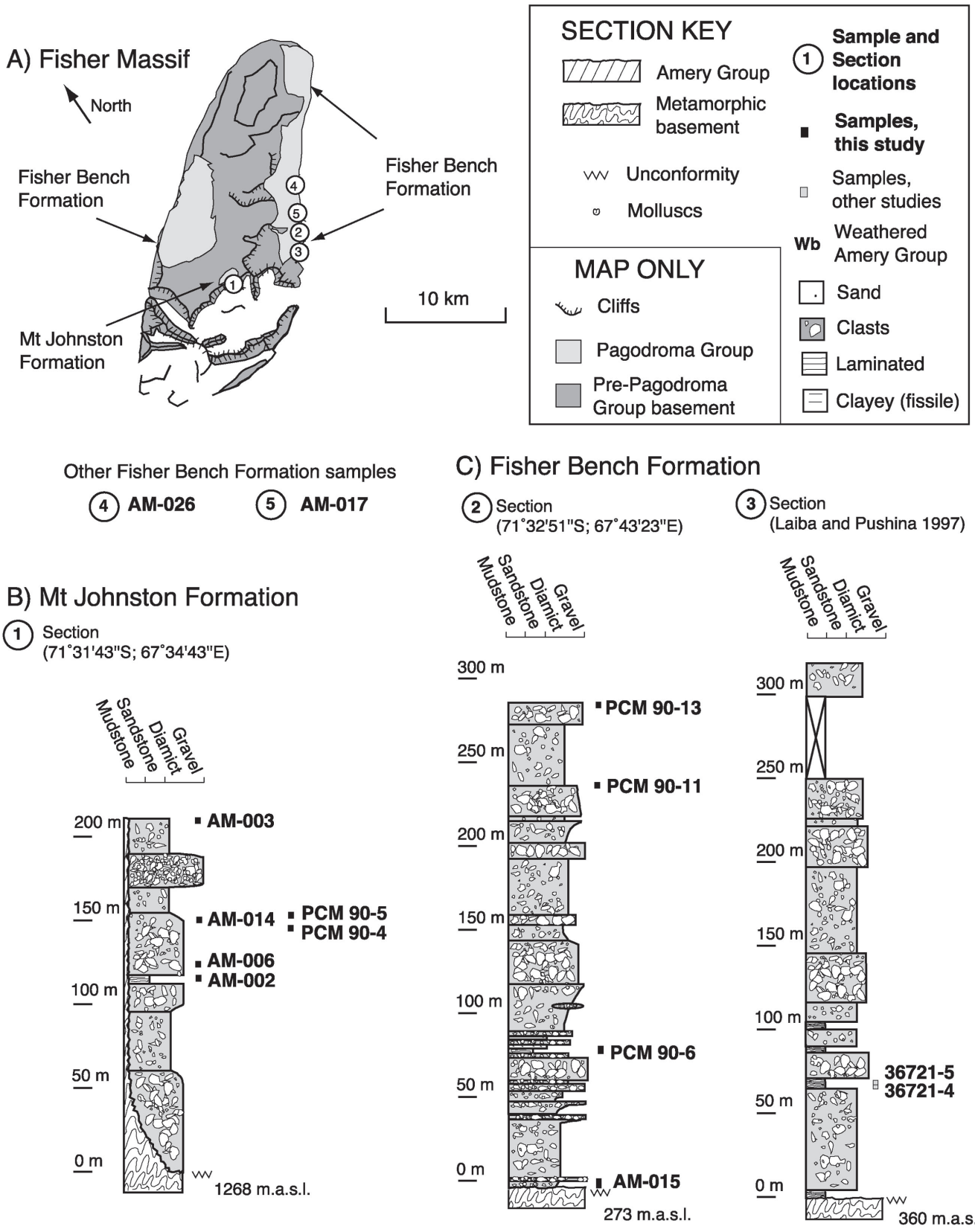

Figure 2. (a) Location of Pagodroma Group sections at Fisher Massif. (b) Mt Johnston Formation and (c) Fisher Bench Formation sections and sample positions. Sections 1 and 2 are from Hambrey and McKelvey (2000a) and section 3 is from Laiba and Pushina (1997). Gravel and diamict are distinguished from each other texturally, and not by clast/grain size as suggested here. The stratigraphic position of samples analysed in the present study are indicated by black boxes and samples from other studies are indicated by grey boxes (see key).

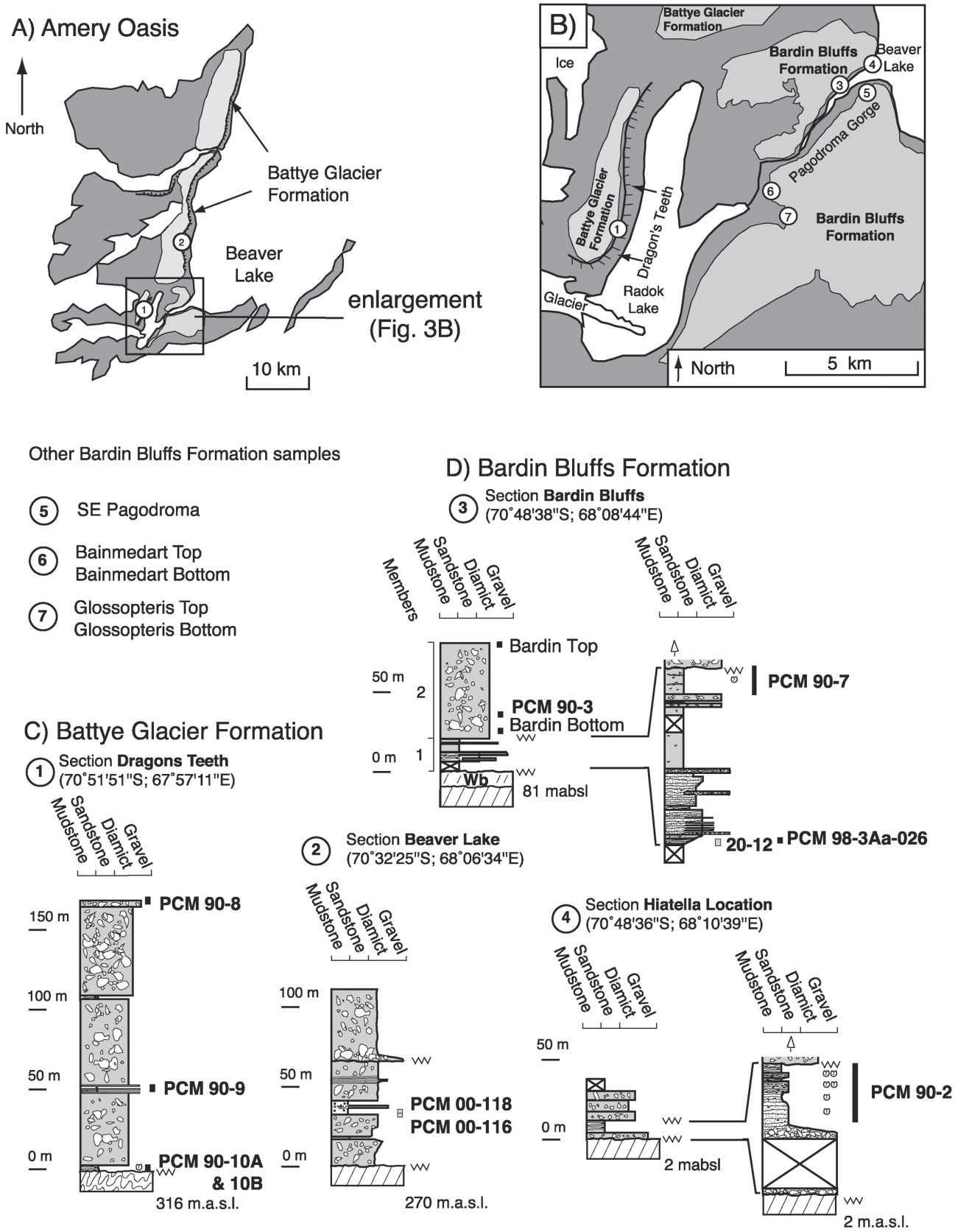

Figure 3. (a) Distribution of the Battye Glacier Formation and (b) Bardin Bluffs Formation at Amery Oasis. (c) Battye Glacier Formation sections and sample positions. (d) Bardin Bluffs Formation sections and sample positions. Section 1 is from Hambrey and McKelvey (2000a) and section 2 is from Whitehead *et al*. (2003) and sections 3 and 4 from Whitehead and McKelvey (2001). Symbols as in Figure 2.

Member 1

In the Member 1 type section at least two mudstone intervals are diatom-bearing (Figure 3d Section 3). Sample PCM 98-3Aa-026 contains numerous benthic diatoms that comprise ~98% of the assemblage. These belong to the genera *Amphora*, *Diploneis*, *Fragilaria*, *Hyalodiscus*, *Melosira*, *Navicula*, *Pinnularia* and *Trachyneis*. The remainder of the assemblage are planktic species. Biogenic silica analysis of sample PCM 98-3Aa-026 indicates ~2% opal (Table 1). A similar diatom assemblage was recorded from this same section by Bardin and Belevich (1985 sample 20-12). However, they identified planktic taxa such as *Actinocyclus actinochilus* (Ehrenberg) Simonsen (reported by them as *Charcotia actinochilus*) and *Thalassiosira antarctica* Comber, which are not observed in PCM 98-3Aa-026. The stratigraphically higher mudstone interval (sample PCM 90-7: Figure 3d Section 3) contains ~1% opal. This diatom assemblage is of biostratigraphically mixed ages, as shown by the co-occurrence of *A. actinochilus* (3.1 Ma: Holocene) and *Fragilariopsis praeinterfrigidaria* (McCollum) Gersonde & Bárcena (5.8–3.6 Ma). The assemblage is almost exclusively of planktic taxa, with the exception of one benthic specimen of *Cocconeis pinnata* Gregory. Diatoms were also recovered from Member 1 mudstone (sample PCM 90-2) at the "Hiatella location" (Figure 3d Section 4). This assemblage consists largely of extant planktic diatoms, with the exception of extinct *A. ingens* and *Rouxia isopolica* Schrader (Table 1). Some diatoms observed in sample PCM 90-2 occur in diatom-rich mudstone clasts (Appendix 2*). These clasts contain a higher abundance of diatoms than the surrounding mud matrix. The overall biogenic silica concentration of sample PCM 90-2 is ~2% opal.

Member 2

Many of the diamicts in Member 2 of the Bardin Bluffs Formation contain diatoms. The diatoms are predominantly planktic marine taxa. Mixing of diatoms of different ages was noted in five samples, e.g. "Bardin Top" (Figure 3d Section 3), and "Glossopteris Top," "Glossopteris Bottom," "Pagodroma SE," and "Bainmedart Top" (Figure 3b). These different-aged diatoms included Pliocene–Quaternary *Fragilariopsis kerguelensis* (O'Meara) Hasle, Pliocene *F. praeinterfrigidaria*, Miocene–Pliocene *Denticulopsis hustedii* (Simonsen & Kanaya) Simonsen, Miocene *Denticulopsis dimorpha* (Schrader) Simonsen, *Denticulopsis praedimorpha* Barron ex Akiba and Eocene–Oligocene *Pyxilla* sp. fragment (Table 1). In sample "Glossopteris Top," centric diatoms and a silicoflagellate contain diatomaceous sediment within their valves and intraskeletal spaces, respectively. In addition, some diatoms occur as diatom-rich clasts, which are more biogenic than the host mud-matrix. The diamict assemblages also include sparse planktic freshwater diatoms of the genera *Cyclotella*, *Stephanodiscus* and *Aulacoseira*, a specimen of *Tabellaria fenestrata* (Lyngb.) Kützing, and a freshwater diatomaceous clast was recovered from sample "Bainmedart Bottom" (Harper & Harwood 1992).

Discussion

The following discussion contains two sections. The first section, Diatom taphonomy, reviews the diatom data in order to identify the most likely mode of microfossil emplacement within the Pagodroma Group. The second section, Diatom biostratigraphy, discusses the assemblage composition in a biostratigraphic context, in order to provide age control for the individual formations of the Pagodroma Group.

Diatom taphonomy

Controversy surrounds the origins of diatoms found in outcrops of Cenozoic sedimentary strata in Antarctica (Miller & Mabin 1998). This controversy has centered on the interpretation of diatoms within diamicts of the Sirius Group in

Figure 4. Southeastern face of Fisher Massif. View looking west. More than 320 m of Miocene Fisher Bench Formation overlying at 270 m above sea-level Proterozoic metavolcanic basement. In the background (center-right) the Cenozoic strata abut the same basement. The planar unconformity surface (small arrows) is a palaeofjord floor. However, in the most western part of the exposure (long arrow), the palaeofjord floor has become inclined and rises steeply as the palaeofjord wall. Asterisks indicate the top and bottom of the Fisher Bench Formation type section (see Figure 2c).

the Transantarctic Mountains. Various processes have been proposed to explain these occurrences. Initially the diatoms were considered to be glacially reworked from now subglacial marine basins (Webb *et al*. 1983; Harwood 1986a,b; Scherer 1989, 1991; Harwood & Webb 1998; Scherer *et al*. 1998; Tulaczyk *et al*. 1998). However, a counterargument is the contamination of outcrops by airborne diatoms. Wind erosion of diatom-bearing marine strata, and diatoms blown from marine and lake environments, are the alternative microfossil sources suggested (Burckle *et al*. 1988, 1997; Barrett 1996; Kellogg & Kellogg 1996; Stroeven *et al*. 1996; Barrett *et al*. 1997). Furthermore, such aeolian processes may also deposit reworked diatoms onto the Antarctic ice sheet, to be eventually incorporated into later glacial deposits (Burckle *et al*. 1997). Another mechanism suggested for airborne diatom contamination is the Eltanin asteroid impact event in the Southern Ocean at *ca* 2.15 Ma (Gersonde *et al*. 1997). This asteroid impacted Cenozoic marine strata spanning the last 50 million years, and the consequent fallout could well have spread diatom-bearing ejecta widely over Antarctica. However, definite *in situ* biogenic marine deposition is now established for the Sørsdal Formation in the Vestfold Hills, some 400 km northeast of the Amery Oasis (Harwood *et al*. 2000; Whitehead *et al*. 2001). In view of this controversy and to help understand the mechanism for microfossil emplacement in the Pagodroma Group, its diatom assemblages and fossil size data have also been compared to similar data from Southern Ocean islands air samples (Chalmers *et al*. 1996), Antarctic ice cores (Burckle *et al*. 1988; Kellogg & Kellogg 1996) and the Sirius Group (Harwood & Webb 1998) (see below). We consider that *in situ* marine deposition and glacial reworking of older glacigene strata best explains diatom emplacement in the Pagodroma Group.

Glacial Reworking

Glacial reworking clearly is a mode of emplacement for some of the Pagodroma Group diatoms. For example, biostratigraphic and ecological mixing of freshwater and marine species, along with poor preservation and the occurrence of diatomaceous clasts in the Bardin Bluffs Formation, point to diatoms sourced by glacial reworking of older sediment. Similarly, reworked shell fragments in diamict (Bardin & Kolosova 1988; Adamson & Darragh 1991) and within sediment clasts in diamict (Stilwell *et al*. 2002) identify glacially reworked molluscs in the Pagodroma Group.

In Situ Marine Deposition

Marine mollusc fossils in the Battye Glacier and Bardin Bluffs Formations provide indisputable evidence for past marine deposition in the Lambert Graben. The mollusc valves generally occur in mudstones. Some valves are still articulated and in growth position (Whitehead *et al*. 2003). Others occur as scattered valves, sometimes crushed, in thinly laminated mudstone (Bardin & Chepaljiga 1989). The molluscs are clearly *in situ* and their co-occurrence or close stratigraphic proximity to diatom-bearing samples strongly supports *in situ* marine deposition of these latter microfossils. Examples of such are the Battye Glacier Formation diatom-rich samples PCM 00-116, and PCM 00-118 (Whitehead *et al*. 2003), the Bardin Bluffs Formation samples PCM 98-3Aa-26 and 20-12 (Table 3). The Battye Glacier Formation sample PCM 00-118 contains up to 12% opal (Whitehead *et al*. 2003) and thus is comparable to sea-floor sediments from many open-marine areas on the present Antarctic continental shelf (Dunbar *et al*. 1989; Harris *et al*. 1997). However, most of the samples assessed for biogenic silica have <3% opal, which is near or below the detection limit of the Mortlock and Froelich (1989) method used in the present study.

Aeolian Contamination

We have evaluated the potential for an aeolian origin of the Pagodroma Group diatom assemblages by comparing them with aeolian assemblages found in Antarctic continental ice cores (<20 000 years old). These ice-core diatoms have been blown onto the Antarctic ice sheets, and are predominately small freshwater and benthic marine taxa (Burckle *et al*. 1988; Kellogg & Kellogg 1996; Harwood & Webb 1998). At least 50% of the South Pole ice-core diatoms are benthic marine/brackish and freshwater taxa (Kellogg & Kellogg 1996). This aeolian assemblage contrasts with the predominantly marine planktic assemblages in most of the Pagodroma Group samples (Tables 1, 3).

Chemical and isotopic analyses of dust particles (<25 μm) in Antarctic ice cores have identified South America as the principal source of aeolian material deposited in Antarctica (Gaudichet *et al*. 1986, 1988; Grousset *et al*. 1992; Delmas & Petit 1994; Basile *et al*. 1997). The northern migration of the Antarctic Polar Front around the southern tip of South America causes the entrainment of dust by storms, which transport it to Antarctica (Burckle *et al*. 1988). This would suggest that the majority of aeolian diatoms delivered to Antarctica have also come from South America (Harwood & Webb 1998). The South Pole ice-core diatoms have been identified as predominately endemic Antarctic marine taxa (Kellogg & Kellogg 1996), but most of the species are also compatible with a South American lake and adjacent marine biogeography (Hallegraeff 1986; Armand 1998; Kellogg & Kellogg 2002).

Local Antarctic aeolian sources can adequately account for the small number of extant endemic Southern Ocean species recovered from ice cores. These include *Fragilariopsis curta* (Van Heurck) Hasle, *F. kerguelensis*, *Fragilariopsis obliquecostata* (Van Heurck) Heiden in Heiden & Kolbe, and *Fragilariopsis sublinearis* (Van Heurck) Heiden (Burckle *et al*. 1988; Kellogg & Kellogg 1996). The diatoms have been either reworked from Antarctic sediment exposures, released from the ocean surface (Kellogg & Kellogg 1996), or else ablated from sea ice.

Aeolian-sourced extinct marine taxa in the Antarctic ice cores, although rare, include the cosmopolitan species *A. ingens*, *Actinoptycus senarius* Ehrenberg, *D. hustedtii* and *Stephanopyxis turris* (Greville & Arnott) Ralfs in Pritchard, and the Southern Ocean endemic taxa *Thalassiosira insigna* (Jousé) Harwood & Maruyama, *Thalassiosira torokina* Brady and *Thalassiosira vulnifica* (Gombos) Fenner (Burckle *et al*. 1988; Kellogg & Kellogg 1996). Scarce extinct freshwater taxa recovered from Bardin Bluffs Formation and Fisher Bench For-

Table 1. Siliceous microfossil data from the Pagodroma Group (present study) and from previous studies (Bardin & Belevich 1985; Laiba & Pushina 1997; Whitehead *et al.* 2003).

Formations	Bardin Bluffs											Battye Glacier		
Sample location	1	1	5	5	3	4	4	2	1	1	1	6	6	6
Sample name	Bardin	Bardin	Gloss.	Gloss.	Pago	Bain.	Bain.	PCM	PCM	PCM	PCM	PCM	PCM	PCM
Sample position/number	top	bottom	top	bottom	SE	top	bottom	90-2	90-3	90-7	98	90-8	90-10A	90-10B
Lithology	Dm	Dm	Dm	Dm	Dm	Dm	Dm	Mud.	Dm	Mud.	Mud.	Dm	Dm	Dm
Diatom abundance	3	4	4	3	4	3	3	4	0	5	6	1	0	1
Raw or concentrated slides	conc.	conc.	conc.	conc.	conc.	conc.	conc.	conc.	conc.	conc.	raw	conc.	conc.	conc.
Biogenic silica (% opal)	-	-	-	-	-	-	-	2%	-	1%	2%	-	-	-
Diatoms: planktic marine														
Actinocyclus actinochilus	-	-	-	-	-	-	-	-	-	2	-	-	-	-
Actinocyclus ingens	2	5	4	1	3	-	2	1	-	-	-	-	-	-
Actinocyclus ingens var. *nodus*	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Actinocyclus aff. *ingens*	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Actinocyclus karstenii	1	-	-	-	-	-	-	-	-	1	-	-	-	-
Actinocyclus octonarius var. *asteriscus*	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Actinoptycus senarius	-	-	-	-	-	-	-	-	-	1	-	-	-	-
Actinoptycus sp. A	-	-	-	-	-	-	-	-	-	1	-	-	-	-
Actinoptycus spp. (fragments)	-	-	-	-	-	-	-	1	-	1	-	-	-	-
Astromphalus spp. (fragments)	-	-	-	-	-	-	-	-	-	1	-	-	-	-
Azpeitia tabularis	1	-	1	-	-	-	-	-	-	-	-	-	-	-
Chaetoceros lorenzianus	-	-	-	-	-	-	-	-	-	-	r	-	-	-
Chaetoceros mitra	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Chaetoceros subsecundus	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Chaetoceros spp. (cyst)	1	-	-	-	2	-	-	2	-	6	2	-	-	-
Chaetoceros spp. (setae)	1	-	-	-	1	-	-	1	-	12	-	-	-	-
Chaetoceros sp. A (setae)	-	-	-	-	-	-	-	-	-	1	1	-	-	-
Coscinodiscus oculus-iridis	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Coscinodiscus oculoides	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Coscinodiscus marginatus	-	1	2	1	-	-	1	-	-	1	-	-	-	-
Coscinodiscus radiatus	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Coscinodiscus sp. A	1	-	-	-	-	-	-	-	-	-	-	-	-	-
Coscinodiscus spp. (whole and frags.)	-	-	-	-	-	-	-	-	-	-	10+	-	-	-
Dactyliosen antarcticus	1	-	6	3	2	1	1	1	-	1	-	-	-	-
Denticulopsis delicata	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Denticulopsis dimorpha	4	-	2	2	-	1	-	-	-	-	-	-	-	-
Denticulopsis hustedtii	-	-	1	-	-	-	-	-	-	-	-	-	-	-
Denticulopsis ovata	2	-	1	2	1	3	-	-	-	-	-	-	-	-
Denticulopsis praedimorpha	1	-	-	-	-	-	-	-	-	-	-	-	-	-
Denticulopsis simonsenii	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Denticulopsis vulgaris	1	-	1	-	-	-	-	-	-	-	-	-	-	-
Denticulopsis spp. (fragments)	3	-	2	-	-	-	2	-	-	1	-	-	-	-
Eucampia antarctica	1	-	1	1	1	-	-	-	-	11	-	-	-	-
Eunotia sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fragilariopsis curta	-	-	-	-	1	-	-	-	-	-	-	-	-	-
Fragilariopsis interfrigidaria	-	1	-	-	-	-	-	-	-	-	-	-	-	-
Fragilariopsis kerguelensis	-	1	1	1	1	-	1	-	-	-	-	-	-	-
Fragiliariopsis praeinterfrigidaria	-	-	1	-	1	-	-	-	-	1	-	-	-	-
Fragiliariopsis sublinearis	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fragilariopsis spp. (fragments)	19	27	70	11	1	5	1-4	-	-	3	-	-	-	-
Nitzschia cholonii	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nitzschia delicatissima	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nitzschia frustulum	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nitzschia sp. A	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nitzschia reinholdii	-	-	-	2	-	-	-	-	-	1	-	-	-	-
Nitzschia sp.	-	-	-	-	-	-	-	-	-	-	r	-	-	-
Odontella weissflogii	-	-	-	-	-	-	-	-	-	-	-	-	-	-

	Fisher Bench						Mt Johnston						Previous studies			
													Bardin	Battye		Fisher
6	9	9	9	9	8	7	10	10	10	10	10	10	1	11	11	9
AM	PCM	PCM	PCM	AM	AM	AM	PCM	PCM	AM	AM	AM	AM		PCM	PCM	PCM
028	90-6	90-11	90-13	015	017	026	90-4	90-5	002	003	006	014	20-12	00-116	00-118	3672
Dm	Mud.	Dm	Dm	Mud.	Dm	Dm	Dm	Dm	Dm	Dm	Dm	Dm	Mud.	Mud.	Mud.	Mud.
0	1	4	0	6	4	1	1	1	0	1	2	1	6	6	6	5
conc.	conc.	conc.	conc.	raw	conc.	conc.	conc.	conc.	conc.	conc.	conc.	conc.	raw	raw	raw	conc.
-	1%	1%	-	~2%	-	1%	-	-	-	-	-	-	-	7%	12%	-
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Table 1. continued.

Formations	Bardin Bluffs											Battye Glacier		
Sample location	1	1	5	5	3	4	4	2	1	1	1	6	6	6
Sample name	Bardin	Bardin	Gloss.	Gloss.	Pago	Bain.	Bain.	PCM	PCM	PCM	PCM	PCM	PCM	PCM
Sample position/number	top	bottom	top	bottom	SE	top	bottom	90-2	90-3	90-7	98	90-8	90-10A	90-10B
Lithology	Dm	Dm	Dm	Dm	Dm	Dm	Dm	Mud.	Dm	Mud.	Mud.	Dm	Dm	Dm
Diatom abundance	3	4	4	3	4	3	3	4	0	5	6	1	0	1
Raw or concentrated slides	conc.	conc.	conc.	conc.	conc.	conc.	conc.	conc.	conc.	conc.	raw	conc.	conc.	conc.
Biogenic silica (% opal)	-	-	-	-	-	-	-	2%	-	1%	2%	-	-	-
Paralia sulcata	-	-	-	-	1	-	-	-	-	-	-	-	-	-
Paralia sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Proboscia barboi	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pyxilla sp.	-	-	-	-	1	-	-	-	-	-	-	-	-	-
Rhizoslenia hebetata group	-	-	-	1	1	-	-	-	-	1	-	-	-	-
Rhizosolenia styliformis group	-	-	-	1	1	-	-	-	-	1	-	-	-	-
Rhizosolenia spp. (fragments)	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Rouxia heteropolara	-	1	-	-	-	-	-	-	-	-	-	-	-	-
Rouxia isopolica	-	-	-	-	-	-	-	1	-	1	-	-	-	-
Rouxia naviculoides	-	-	-	-	-	-	-	-	-	-	6	-	-	-
Rouxia spp. (fragments)	-	-	-	2	1	1	-	1	-	37	-	-	-	-
Stellarima microtrias	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Stellarima stellaris	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Stellarima spp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Stephanopyxis grunowii	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Stephanopyxis splendidus	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Stephanopyxis turris	-	-	-	-	1	-	-	-	-	-	r	-	-	-
Stephanopyxis sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Synedropsis sp.	-	-	-	-	-	-	-	-	-	-	r	-	-	-
Thalassiothrix sp. (fragments)	1	-	2	1	1	-	1	-	-	-	-	1	-	1
Thalassiothrix / *Thalassionema* (frag.)	12	3	29	30	17	12	9	49	-	218	-	-	-	-
Thalassionema nitzschioides	-	-	-	-	-	-	-	20	-	29	r	-	-	-
Thalassionema nitzschioides var. *parva*	-	-	-	-	-	-	-	3	-	1	-	-	-	-
Thalassiosira Antarctica	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Thalassiosira gracils var. *gracilis*	-	-	-	-	-	1	-	-	-	-	-	-	-	-
Thalassiosira insigna	-	-	-	1	-	-	-	-	-	-	-	-	-	-
Thalassiosira inura	-	-	-	-	-	-	1	-	-	-	-	-	-	-
Thalassiosira nativa	1	-	-	-	-	-	-	1	-	X	-	-	-	-
Thalassiosira oliverana	-	-	1	1	-	-	-	1	-	-	-	-	-	-
Thalassiosira oestrupii	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Thalassiosira sp. (concentric areolae)	-	-	-	-	-	-	-	1	-	-	-	-	-	-
Thalassiosira spp. (fragments)	-	-	-	-	-	-	-	-	52	-	-	-	-	-
Diatoms: benthic marine														
Achnanthes brevipes	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Amphora spp.	-	-	-	-	-	-	-	-	-	-	124	-	-	-
Anaulus sp.	-	-	-	-	-	-	-	-	-	-	1	-	-	-
Caloneis sp.	-	-	-	-	-	-	1?	-	-	-	-	-	-	-
Cocconeis sp A.	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Cocconeis costata	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Cocconeis fasciolata	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Diploneis frickei	-	-	-	-	-	-	-	-	-	-	4	-	-	-
Diploneis oculata ?	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Diploneis subovalis	-	-	-	-	-	-	-	-	-	-	18	-	-	-
Diploneis smithii ?	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Diploneis bomboides	-	-	-	-	-	-	-	-	-	-	12	-	-	-
Diplonies and *Navicula* sp. (fragments)	3	-	4	1	2	-	-	-	-	1	r	-	-	-

	Fisher Bench						Mt Johnston						Previous studies			
													Bardin	Battye		Fisher
6 AM 028 Dm 0 conc. -	9 PCM 90-6 Mud. 1 conc. 1%	9 PCM 90-11 Dm 4 conc. 1%	9 PCM 90-13 Dm 0 conc. -	9 AM 015 Mud. 6 raw ~2%	8 AM 017 Dm 4 conc. -	7 AM 026 Dm 1 conc. 1%	10 PCM 90-4 Dm 1 conc. -	10 PCM 90-5 Dm 1 conc. -	10 AM 002 Dm 0 conc. -	10 AM 003 Dm 1 conc. -	10 AM 006 Dm 2 conc. -	10 AM 014 Dm 1 conc. -	1 20-12 Mud. 6 raw -	11 PCM 00-116 Mud. 6 raw 7%	11 PCM 00-118 Mud. 6 raw 12%	9 PCM 3672 Mud. 5 conc. -
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
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Table 1. continued.

Formations	Bardin Bluffs											Battye Glacier		
Sample location	1	1	5	5	3	4	4	2	1	1	1	6	6	6
Sample name	Bardin	Bardin	Gloss.	Gloss.	Pago	Bain.	Bain.	PCM	PCM	PCM	PCM	PCM	PCM	PCM
Sample position/number	top	bottom	top	bottom	SE	top	bottom	90-2	90-3	90-7	98	90-8	90-10A	90-10B
Lithology	Dm	Dm	Dm	Dm	Dm	Dm	Dm	Mud.	Dm	Mud.	Mud.	Dm	Dm	Dm
Diatom abundance	3	4	4	3	4	3	3	4	0	5	6	1	0	1
Raw or concentrated slides	conc.	conc.	conc.	conc.	conc.	conc.	conc.	conc.	conc.	conc.	raw	conc.	conc.	conc.
Biogenic silica (% opal)	-	-	-	-	-	-	-	2%	-	1%	2%	-	-	-
Fragilaria spp	-	-	-	-	-	-	-	-	-	-	1	-	-	-
Grammatophora spp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Hyalodiscus valens	-	-	-	-	-	-	-	-	-	-	12	-	-	-
Hyalodiscus obsoletus	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Hyalodiscus zonulatus	-	-	-	-	-	-	-	-	-	-	14	-	-	-
Hyalodiscus sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Isthmia sp. (fragments)	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Melosira sp.	-	-	-	-	-	-	-	-	-	-	205	-	-	-
Podosira sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Navicula cryophila	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Navicula directa	-	-	-	-	-	-	-	-	-	-	r	-	-	-
Navicula glaciei	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Navicula retusa	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Navicula spp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nitzschia acicularis	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nitzschia scabra	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Porosira antarctica	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Porosira pseudeodenticulata	-	-	-	-	-	-	-	-	-	-	1	-	-	-
Pinnularia quadratea	-	-	-	-	-	-	-	-	-	19	-	-	-	-
Rhabdonema japonica group	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Rhabdonema sp. cf. *R. elegans*	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Rhabdonema spp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Rhaphoneis spp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Stictodiscus hardmanianus	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Synedra sp.	-	-	-	-	-	-	-	-	-	-	r	-	-	-
Trachyneis aspera	-	-	-	-	-	-	-	-	-	7	-	-	-	-
Triceratium oamaruense var. *sparsipunctatum*	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Trinacria excavata	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Trigonium arcticum	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Gen. et sp. B (of Harwood (1986a))	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Diatoms: benthic, possible non-marine														
Amphora sp. A	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Cocconeis pinnata (non-marine?)	-	-	-	-	-	-	-	-	-	1	-	-	-	-
Diploneis sp. A	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Gomphonema angustatum var. A	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Gomphonema angustatum var. B	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tabellaria fenestrata	-	-	1	-	-	-	-	-	-	-	-	-	-	-
Tabellaria sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Aulacoseira sp.	-	-	-	-	-	1	-	-	-	-	-	-	-	-
Cyclotella sp.	3	-	21	-	-	-	-	-	-	-	-	-	-	-
Stephanodiscus spp.	-	-	-	-	1	1	1	-	-	-	-	-	-	-
Diatomaceous aggregates	-	2	3	5	2	-	1	23	-	-	-	-	-	-

	Fisher Bench						Mt Johnston						Previous studies			
													Bardin	Battye		Fisher
6 AM 028 Dm 0 conc. -	9 PCM 90-6 Mud. 1 conc. 1%	9 PCM 90-11 Dm 4 conc. 1%	9 PCM 90-13 Dm 0 conc. -	9 AM 015 Mud. 6 raw ~2%	8 AM 017 Dm 4 conc. -	7 AM 026 Dm 1 conc. 1%	10 PCM 90-4 Dm 1 conc. -	10 PCM 90-5 Dm 1 conc. -	10 AM 002 Dm 0 conc. -	10 AM 003 Dm 1 conc. -	10 AM 006 Dm 2 conc. -	10 AM 014 Dm 1 conc. -	1 20-12 Mud. 6 raw -	11 PCM 00-116 Mud. 6 raw 7%	11 PCM 00-118 Mud. 6 raw 12%	9 PCM 3672 Mud. 5 conc. -
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	F	F	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	R	
-	-	1	-	1	-	1	-	-	-	-	-	-	-	-	-	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	
-	-	-	-	-	-	-	-	-	-	-	-	-	some	-	-	
-	-	-	-	-	-	-	-	-	-	-	-	-	25-30	-	-	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	R	
-	-	-	-	-	-	-	-	-	-	-	-	-	1-10	-	-	
-	-	-	-	-	-	-	-	-	-	-	-	-	1-5	-	-	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
-	-	-	-	-	-	-	-	-	-	-	-	-	1-5	-	-	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	
-	-	-	-	-	-	-	-	-	-	-	-	some /T	X	R		
-	-	-	-	1	-	-	-	-	-	-	-	-	-	R	X	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	F	R	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	R	-	
-	-	1	-	r	1	-	-	-	-	-	-	-	-	-	-	
-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	
-	-	-	-	-	-	-	-	-	-	-	-	-	R	X		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	
-	-	-	-	1	1	-	-	-	-	-	-	-	-	-	-	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	
-	-	-	-	r	-	-	-	-	-	-	-	-	-	-	-	
-	-	7	-	-	-	-	-	-	-	-	-	-	-	-	-	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	
-	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-	
-	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	R	F	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
-	-	X	-	1	-	-	-	-	-	-	-	-	-	-	-	

Table 1. continued.

Formations	Bardin Bluffs											Battye Glacier		
Sample location	1	1	5	5	3	4	4	2	1	1	1	6	6	6
Sample name	Bardin	Bardin	Gloss.	Gloss.	Pago	Bain.	Bain.	PCM	PCM	PCM	PCM	PCM	PCM	PCM
Sample position/number	top	bottom	top	bottom	SE	top	bottom	90-2	90-3	90-7	98	90-8	90-10A	90-10B
Lithology	Dm	Dm	Dm	Dm	Dm	Dm	Dm	Mud.	Dm	Mud.	Mud.	Dm	Dm	Dm
Diatom abundance	3	4	4	3	4	3	3	4	0	5	6	1	0	1
Raw or concentrated slides	conc.	conc.	conc.	conc.	conc.	conc.	conc.	conc.	conc.	conc.	raw	conc.	conc.	conc.
Biogenic silica (% opal)	-	-	-	-	-	-	-	2%	-	1%	2%	-	-	-
Dinoflagellates														
Actiniscus pentasteris	-	-	-	-	-	-	-	-	-	5	-	-	-	-
Silicoflagellates														
Distephanus spp.	-	-	1	-	1	-	-	1	-	1	-	-	-	-
Ebridians														
Pseudammodochium lingii	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sponge spicules	5	11	4	1	6	2	-	-	-	1	r	-	-	1
Radiolaria	-	-	2	1	2	1	1	-	-	-	-	-	-	-
Chrysophytes	3	5	-	-	1	-	-	-	-	-	-	-	-	-

Numbers represent fossil (intact and fragments) observed. Up to 400 diatom specimens (represented by more than half the valve present) were recorded from samples PCM 98-3Aa-26 and AM-015. The symbol 'r' denotes other rare species within these samples, while 'r?' signifies uncertain taxonomy of a rare fragment. Other abbreviations: Bardin, Bardin Bluffs; Gloss., Glossopteris; Pago., Pagodroma; Bain., Bainmedart; Battye, Battye Glacier; Fisher, Fisher Bench; Dm, diamict; Mud., mudstone; conc., concentrated. Underlined species are those only identified in previous studies. Previous Bardin Bluffs Formation sample data are number of specimens seen in the preparation and per traverse of the slide (/T). Abbreviations in previous Battye Glacier Formation sample data are: C, >1 valve per field of view; F, >1 valve per 10 fields of view; R, 3 valves in the preparation; X, 1 valve in the preparation. Abbreviations in previous Fisher Bench Formation data are: VR, 1 valve in the preparation; R, 1–10 valves in the preparation; F, 1–3 per traverse of slide. opal, biogenic silica. Some data from Whitehead *et al*. (2003) have been omitted because they do not help to further constrain the biostratigraphic age.

mation samples (e.g. "Bainmedart Bottom" and PCM 90-11) may also be aeolian contaminants. However, exposures of diatomaceous strata suitable to source (for aeolian transport) the several extinct species of diverse ages found in the Pagodroma Group are not yet known in Antarctica; neither do the Pagodroma Group diatom assemblages resemble the aeolian assemblages found in ice cores. In particular, there is no appreciable component of freshwater taxa (Table 3). For these two reasons we consider any aeolian contribution to the Pagodroma Group assemblages not to have been a major one. Furthermore many of the diatomaceous clasts in the Pagodroma Group, and in particular those in the Bardin Bluffs Formation sample PCM 90-2, exceed the particle size of continental loess, and of aeolian dust and diatom material recovered from Antarctic ice cores (Figure 9). Thus such clasts are unlikely to be of aeolian origin.

Asteroid Impact Fallout

It has been suggested the Eltanin asteroid impact in the Southern Ocean at *ca* 2.15 Ma caused the ejection of diatomaceous marine sediment spanning the last 50 million years, and through fallout this material may have been widely redeposited over Antarctica (Gersonde *et al*. 1997). Presumably such fallout would be biostratigraphically mixed, containing planktic marine diatoms spanning the interval between 50 and 2.15 Ma. Samples with biostratigraphically mixed planktic marine species do occur in the Bardin Bluffs Formation (Table 3; Figure 8), but their ages are generally <14.2 Ma and do not span the interval 50–2.15 Ma. However, sample "Pagodroma SE" (of the Bardin Bluffs Formation) produced a single fragment of *Pyxilla* sp., very probably the Southern Ocean species *Pyxilla reticulata* Grove & Sturt, with a last occurrence datum of 30.1 Ma (Scherer *et al*. 2000). Because the time interval between 30.1 and 14.2 Ma is not represented, inheritance through glacial reworking rather than by impact fallout appears to be the more likely interpretation of this fossil. Biostratigraphic mixing of Miocene taxa is apparent in Fisher Bench Formation sample AM-015, where 14.5–12.5 Ma taxa are admixed with 11.7–8.5 Ma taxa (Figure 7) (discussed below). In the absence of both >14.5 Ma and <8.5 Ma diagnostic taxa, glacial reworking would again appear to be a simpler interpretation.

Summary

In the light of the evidence reviewed above we consider the diatom assemblages of the Pagodroma Group to predominantly reflect (i) *in situ* marine deposition and/or (ii) glaciomarine reworking of older Cenozoic strata. In consequence both the non-mixed and mixed biostratigraphic assemblages encountered are to be expected. In arriving at these two conclusions concerning diatom emplacement, we are most strongly influenced by (i) the presence of *in situ* macrofossils in the Battye Glacier Formation and of *in situ* macrofossils and foraminifers in the Bardin Bluffs Formation; (ii) the

	Fisher Bench						Mt Johnston						Previous studies			
													Bardin	Battye		Fisher
6 AM 028 Dm 0 conc. -	9 PCM 90-6 Mud. 1 conc. 1%	9 PCM 90-11 Dm 4 conc. 1%	9 PCM 90-13 Dm 0 conc. -	9 AM 015 Mud. 6 raw ~2%	8 AM 017 Dm 4 conc. -	7 AM 026 Dm 1 conc. 1%	10 PCM 90-4 Dm 1 conc. -	10 PCM 90-5 Dm 1 conc. -	10 AM 002 Dm 0 conc. -	10 AM 003 Dm 1 conc. -	10 AM 006 Dm 2 conc. -	10 AM 014 Dm 1 conc. -	1 20-12 Mud. 6 raw -	11 PCM 00-116 Mud. 6 raw 7%	11 PCM 00-118 Mud. 6 raw 12%	9 PCM 3672 Mud. 5 conc. -
-	-	5	-	-	-	-	-	-	-	-	-	-	-	-	-	
-	-	-	-	r	-	-	-	-	-	-	-	-	-	X	R	
-	-	-	-	13	-	-	-	-	-	-	-	-	-	-	-	
-	-	5	-	12	-	-	-	-	-	-	-	-	-	X	R	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	

frequent absence of biostratigraphic admixing in many samples; (iii) the predominantly planktic composition of most Pagodroma Group diatom assemblages, in marked contrast to the marine planktic, benthic and lacustrine assemblages recovered from polar ice cores (Burckle *et al*. 1988; Kellogg & Kellogg 1996; Harwood & Webb 1998); and (iv) the absence of microfossil assemblages adequately spanning the 50–2.15 Ma interval supposedly encompassed by the Eltanin asteroid fallout. Although some aeolian contamination is very possible, the apparent lack of stratigraphic sources appropriate to account for the Pagodroma Group assemblages, their compositional difference to aeolian assemblages in ice cores, and the as yet palaeontologically unproven status of the suggested Eltanin asteroid fallout contribution, we view any aeolian contribution as being only minor. The glaciomarine depositional scenario proposed for the Pagodroma Group by Hambrey and McKelvey (2000a, b) has been modified (Figure 10) to incorporate both *in situ* marine diatom deposition and glacial reworking processes.

Diatom biostratigraphy

Because the following biostratigraphic discussion assumes that glacial reworking processes may have been operative, the maximum age of most samples can be constrained only to the first occurrence datum of the youngest fossil present.

Mt Johnston Formation

The presence (Table 1) of *Stephanopyxis splendidus* and *Pyxilla* sp. (probably *P. reticulata*) suggests, in the first instance, marine deposition at some time in the Early Oligocene, between *ca* 35 and 33 Ma (Figure 7). However, it is unclear if these Mt Johnston Formation diatoms are *in situ* or are glacially reworked into diamicts (Figure 10). The fact that there is no biostratigraphic mixing with assemblages found in the nearby Middle to Upper Miocene Fisher Bench Formation (discussed below) does restrict deposition of the Mt Johnston Formation to an interval between Early Oligocene (*ca* 35 Ma) and the Middle to Late Miocene (>12.1 Ma).

Fisher Bench Formation

Of the six samples from this formation (Figure 2c; Table 1), only sample PCM 90-13 is barren of diatoms. The microfossils are most abundant in the two mudstone samples AM 015 and 36721-4, the latter sample that of Laiba and Pushina (1997). The relatively high abundance of diatoms in these restricted intervals of fine sediment, and the rarity of diatoms in the associated diamict facies, strongly suggests the mudstone microfossils to be *in situ*.

Diatoms in the basal sample AM-015 suggest deposition in the Middle to Late Miocene. An age between 14.2 and 12.5 Ma was assigned for this sample in McKelvey *et al*. (2001), based on the presence of *Actinocyclus ingens* var. *nodus* Baldauf (first occurrence 14.5 Ma and last occurrence 12.5 Ma) and of *D. simonsenii*, with a first occurrence of 14.2 Ma (now considered to be 14.3 Ma). However, it is possible to further restrict the age to between 11.7 and 8.5 Ma, based on additional data (Figure 7b). This would necessitate interpreting the presence of *A. ingens* var. nodus (first occurrence 12.5 Ma) as a consequence of reworking of older strata. This younger age is supported by the presence of *Denticulopsis ovata* (Schrader) Yanagisawa & Akiba, the range of which spans *ca* 12.11–8.5 Ma. Support for an age of <11.7 Ma for AM-015 comes from the presence of *D. vulgaris*. This species has a first occurrence of 13.0 Ma in the northern Pacific (Yanagisawa & Akiba 1998), but appears later in the Kerguelen Plateau ODP Site 1138A, with a first occurrence in the *D. dimorpha* Zone, i.e. between 11.7 and 10.7 Ma (Bohaty *et al*.

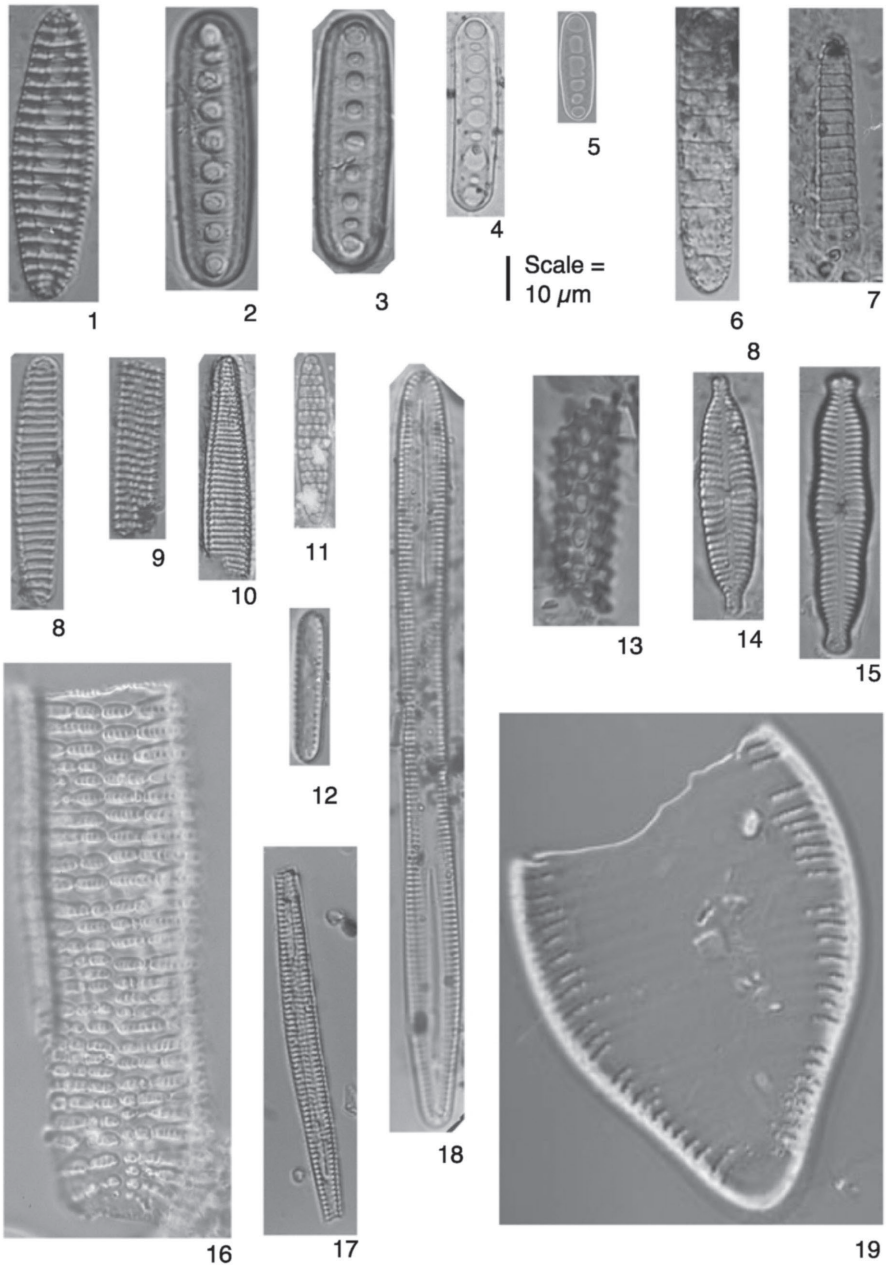

Figure 5. (1) *Denticulopsis hustedtii* (Glossopteris Top). (2, 3) *Denticulopsis dimorpha* (Bardin Top). (4) *Denticulopsis ovata* (Glossopteris Bottom). (5) *Denticulopsis praedimorpha* (Bardin Top). (6) *Denticulopsis simonsenii* (AM-015). (7) *Denticulopsis delicata* fragment (AM-015). (8) *Fragilariopsis praeinterfrigidaria* (Glossopteris Top). (9) *Fragilariopsis interfrigidaria* fragment (Glossopteris Bottom). (10) *Nitzschia reinholdii* fragment (PCM 90-7). (11) *Fragilariopsis kerguelensis* (Glossopteris Top). (12) *Thalassionema nitzschioides* (Glossopteris Bottom). (13) *Pyxilla* sp. probably *Pyxilla reticulata* fragment (AM-006). (14) *Gomphonema angustatum* var. A (PCM 90-11). (15) *Gomphonema angustatum* var. B (PCM 90-11). (16) *Rhabdonema japonica* fragment (AM-015). 17 *Rouxia isopolica* (PCM 90-7). (18) *Rouxia heteropolara* (Bardin Bottom). 19 *Rhaphoneis* sp. (AM-015).

2003). The presence of *Proboscia barboi* (Brün) Jordan & Priddle (first occurrence of 12.7 Ma) in AM-015, further supports an age <12.7 Ma.

Sample 36721–4 (Figure 2c, Section 3) of Laiba and Pushina (1997) contains Miocene marine diatoms including *D. simonsenii*, which constrains the age only broadly to between 14.3 and 4.9 Ma. Sample 36721-4 is also rich in benthic diatoms, suggesting either deposition in a marine environment <50 m deep or else sediment transport by syndepositional slumping of shallow-marine sediments from near the former fjord wall (Laiba & Pushina 1997). Overall, the benthic species in the Fisher Bench Formation support a Neogene age. Sample PCM 90-6 (Figure 2c Section 2) contains a few intact and fragmented diatoms, which add no further age constraint. *Rhabdonema japonica* Tempére & Brün, Gen. et sp. C Harwood (1986a) and *Isthmia* sp. occur in AM-015; *H. obsoletus*, *Rhabdonema* sp. and *Rhaphoneis* spp. occur in 36721-4. Examination of the assemblages in Kellogg and Kellogg (2002) indicates that the above taxa are no longer found in the modern Antarctic environment, but they are present in shallow-marine Neogene sediments in the Ross Sea (Harwood 1986a,b; Harwood *et al*. 1989; Winter 1995; Barrett *et al*. 1998) and in Prydz Bay (Harwood *et al*. 2000; Whitehead *et al*. 2001).

As previously noted, the Fisher Bench Formation diamict sample PCM 90-11 contains two assemblages that contrast in preservation and ecology. The less abundant, but conspicuously well-preserved diatoms (often complete frustules) are the benthic species *Gomphonema angustatum* var. sp. A, *G. angustatum* var. sp. B, *Diploneis* sp. A and *Amphora* sp. A. *Gomphonema angustatum* is a freshwater species (Cramer 1979; Beaver 1981), as could also be the variants *G. angustatum* var.

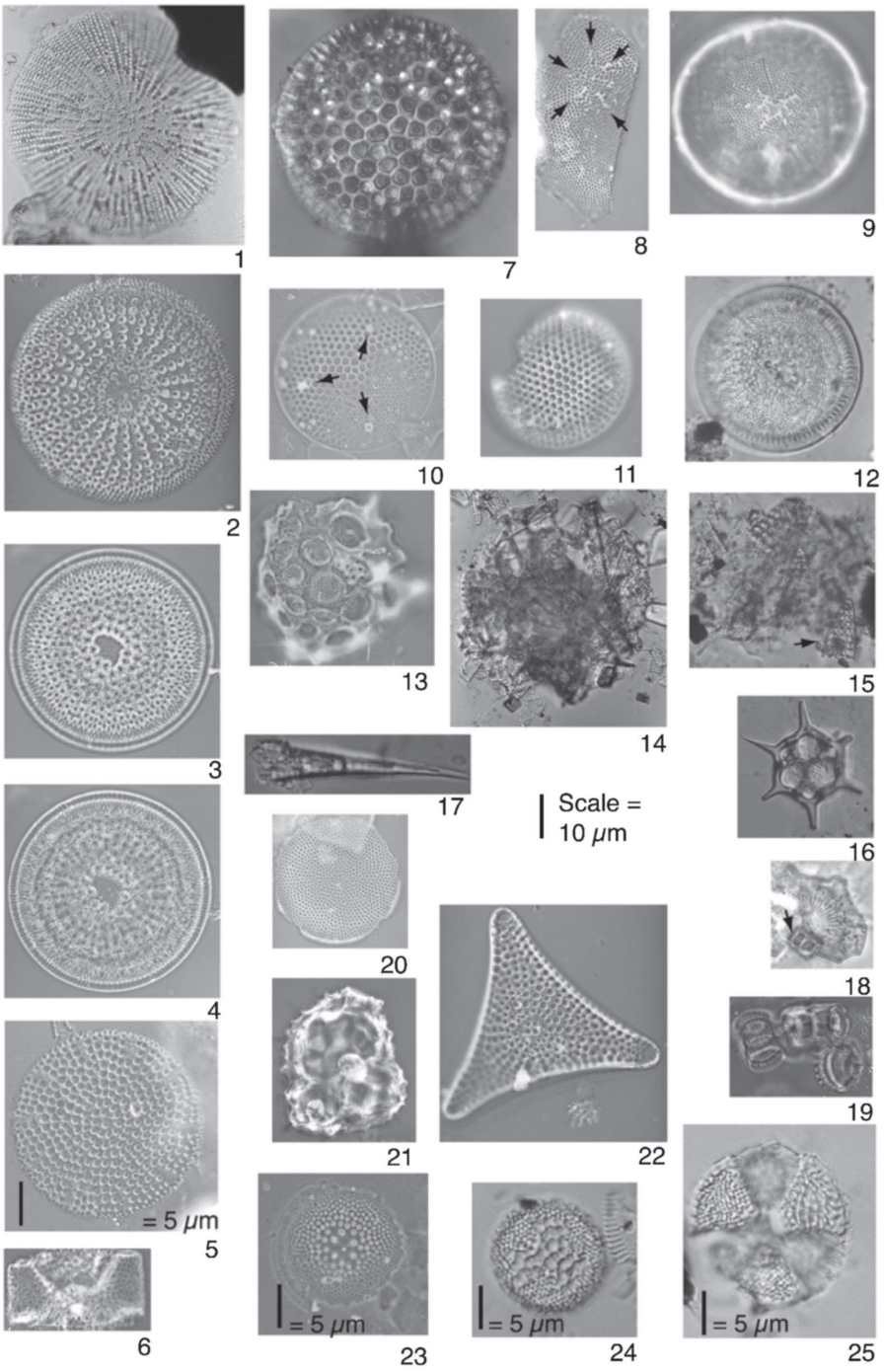

Figure 6. (1) *Actinocyclus actinochilus* (PCM 90-7). (2) *Actinocyclus ingens* (AM-015). (3, 4) *Actinocyclus ingens* var. *nodus* (AM-015). (5) *Actinocyclus karstenii* (Bardin Top). (6) *Eucampia antarctica* (Bardin Top). (7) *Coscinodiscus marginatus* (Bardin Bottom). (8) *Stellarima stellaris* fragment, arrows indicate labiate arrangement and lack of central hyaline area (different to *S. microtrias*) (AM-015). (9) *Stellarima microtrias* (AM-015). (10) *Stephanopyxis splendidus* (arrows indicate distinctive processes) (AM-006). (11) *Stephanopyxis turris* (AM-006). (12) *Thalassiosira oliverana* (Glossopteris Bottom). (13) Radiolarian fragment containing diatomite (Glossopteris Bottom). (14) Diatomaceous aggregate (PCM 90-2). (15) Diatomaceous aggregate with an arrow indicating a fragment of *Fragilariopsis kerguelensis* (Bardin Bottom). (16) Silicoflagellate *Distephanus speculum speculum "pseudofibula* plexus" containing diatomite (Glossopteris Top). (17) *Rhizosolenia hebetata* fragment (PCM 90-7). (18) *Stephanodiscus* spp. fragment and arrow pointing at *Aulacoseira* sp. (Pagodroma SE). (19) *Aulacoseira* sp. (Bainmedart Bottom). (20) *Coscinodiscus* sp. A (AM-015). (21) Ebridian *Pseudammodochium lingii* (AM-015). (22) *Trinacria excavata* (AM-015). (23) *Thalassiosira gracilis* var. *gracilis* (Bainmedart Top). (24) *Actinoptycus* sp. A (PCM 90-7). (25) *Actinoptycus senarius* (PCM 90-7).

sp. A, and *G. angustatum* var. sp. B. While *Amphora* and *Diploneis* are typically marine genera, rare freshwater species do exist, and their association with *G. angustatum* var. spp. A and B suggests that these Fisher Bench diatoms are non-marine species. They possibly originated from lakes discharging into the Lambert Graben during accumulation of Fisher Bench Formation diamicts.

The most abundant diatoms in sample PCM 90-11 are highly fragmented planktic marine taxa. Their fragmented nature suggests glacial reworking, because *in situ* marine deposition should allow for good diatom preservation. Later glacial overriding and sediment shearing can cause diatom breakage (Scherer *et al*. 2001); but the excellent preservation of the associated freshwater taxa in sample PCM 90-11 makes this unlikely. The presence of *P. barboi* constrains the original (source bed) age to <12.7 Ma.

Battye Glacier Formation

The sparse diatom fragments in the Battye Glacier Formation at Dragons Teeth (samples PCM 90-8 and PCM 90-10B: Figure 3c; Table 1) are of the extant planktic marine *Thalassiothrix* sp., the age range of which has not been established. The Dragons Teeth facies are basin-marginal, and are in marked contrast to the Battye Glacier Formation outcrops 13 km to the northeast (Whitehead *et al*. 2003), where more distal diatom-bearing muds contain up to 12% opal (samples

PCM 00-118 and PCM 00-116: Figure 3c Section 2). These are the most biogenic facies known so far in the Pagodroma Group and their abundant benthic diatoms point to a shallow (euphotic) bathymetry. Because the opal content is comparable to that of contemporary marine sediment in Prydz Bay today, biostratigraphic analysis has been undertaken using a similar approach to that used upon open-marine strata, where the absence of taxa helps constrain the age (Figure 8a). That the two samples (PCM 00-116, PCM 00-118) were deposited at some time between 11.7 and 9.0 Ma (Middle to Late Miocene) is indicated by the presence of *D. vulgaris* (first occurrence 11.7–10.7 Ma) and by the absence of *T. torokina* (first occurrence 9.0 Ma) (Whitehead *et al*. 2003). Furthermore, the absence of *D. dimorpha*, which occurs nearby as a reworked component in the younger Bardin Bluffs Formation, suggests constraint of the age to less than *ca* 10.7 Ma (Whitehead *et al*. 2003) (Figure 8).

Bardin Bluffs Formation

The abundant diatoms recovered from the older Member 1 mudstone (sample 20-12 of Bardin & Belevich 1985) (Figure 3), include *Actinocyclus actinochilus*. This extant species (first occurrence 3.1 Ma), indicates that Member 1 was deposited <3.1 Ma (Figure 8b), and the presence of *T. antarctica* could even infer an age <0.67 Ma for Member 1 (Bohaty *et al*. 1998). However, this latter datum has been established from lower latitude oceanic occurrences on the Kerguelen Plateau (Scherer 1991), and it may become diachronously older southwards onto the Antarctic continental shelf where *Thalassiosira antarctica* is currently widespread, and ranges from rare to 15% relative abundance (Armand 1998). Antarctic continental shelf records are disparate and further work is required to determine the oldest age for the first occurrence of *Thalassiosira antarctica*.

An attempt has been made to relocate the field position of sample 20-12; sample PCM 98-3Aa-026 is considered to be close to the sample horizon. Both samples contain a high abundance of benthic diatom taxa, although planktic diatoms are common in sample 20-12. Unfortunately the scarcity of biostratigraphically well-constrained planktic taxa precludes a more precise age determination of the Bardin Bluffs Formation from sample PCM 98-3Aa-026. The high abundance of Antarctic benthic marine diatoms in both of these samples emphasises that deposition occurred in a shallow euphotic environment.

In the younger Member 1 mudstone (sample PCM 90-7: Figures 3, 8b) with its moderately high abundance of intact and fragmented diatoms, *A. actinochilus* again indicates deposition <3.1 Ma. The presence of the foraminifer *Globigerina* sp. cf. *G. antarctica* in PCM 90-7 further constrains the age to between 2.6 and 0.99 Ma (McKelvey *et al*. 2001). Together with the presence of *Actinocyclus karstenii* Van Heurck (last occurrence 2.9–1.8 Ma), these fossils potentially constrain the age of PCM 90-7 to between 2.6 and 1.8 Ma. The diatom assemblage is biostratigraphically mixed, with the co-occurrence of *A. actinochilus* (first occurrence 3.1) and *F. praeinterfrigidaria* (last occurrence 3.6 Ma). We consider *F. praeinterfrigidaria* to have been glacially reworked from Lambert Graben marine strata of between 5.8 and 3.6 Ma in age, and incorporated into this younger Member 1 mudstone.

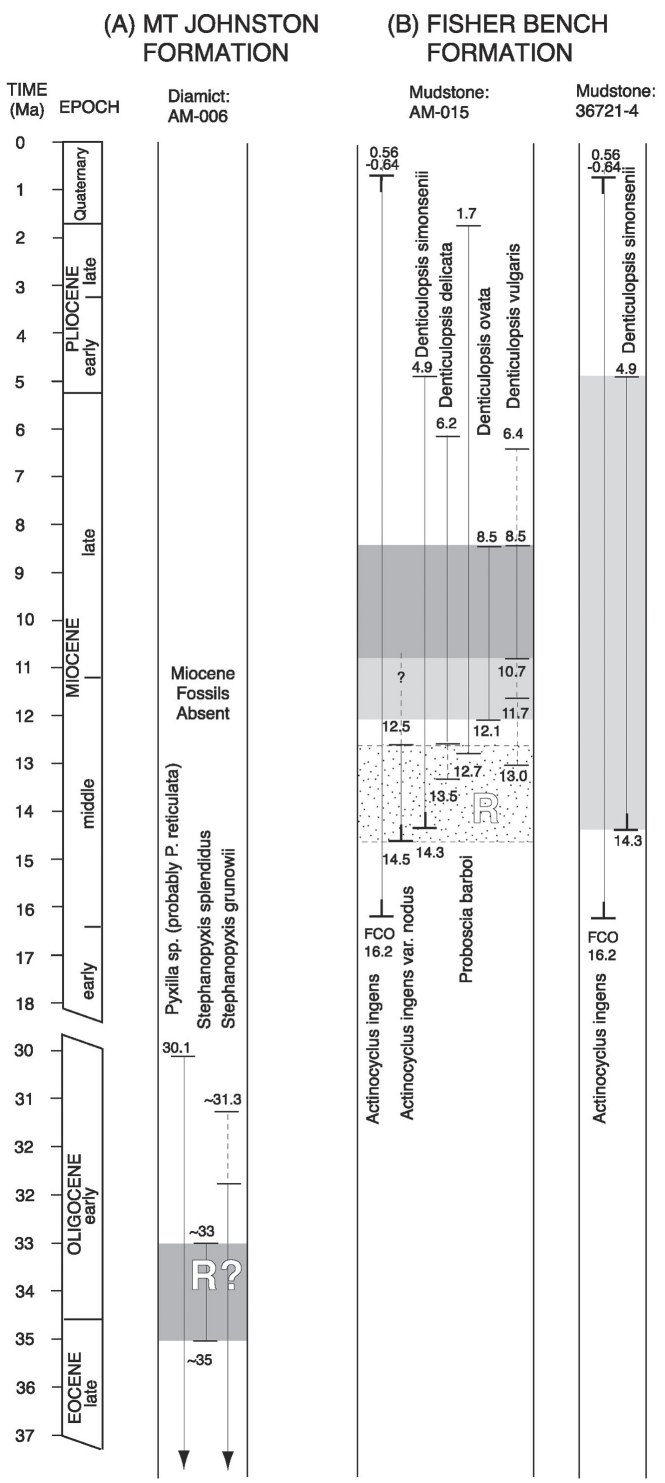

Figure 7. Age ranges inferred from diatom biostratigraphy of the Mt Johnston Formation (AM-006) and Fisher Bench Formation (AM-015, 36721-4). Dark-grey hachure indicates the most constrained age interpretation. Light-grey hachure indicates broader age ranges from other reliable data. Stippled hachure indicates the time range of source areas from where non-*in situ* diatoms have been derived by glacial reworking. The symbol "R?" indicates uncertainty as to whether the sparse flora is *in situ* or else of a reworked origin. The Miocene fossils in the Fisher Bench Formation are absent from the Mt Johnston Formation.

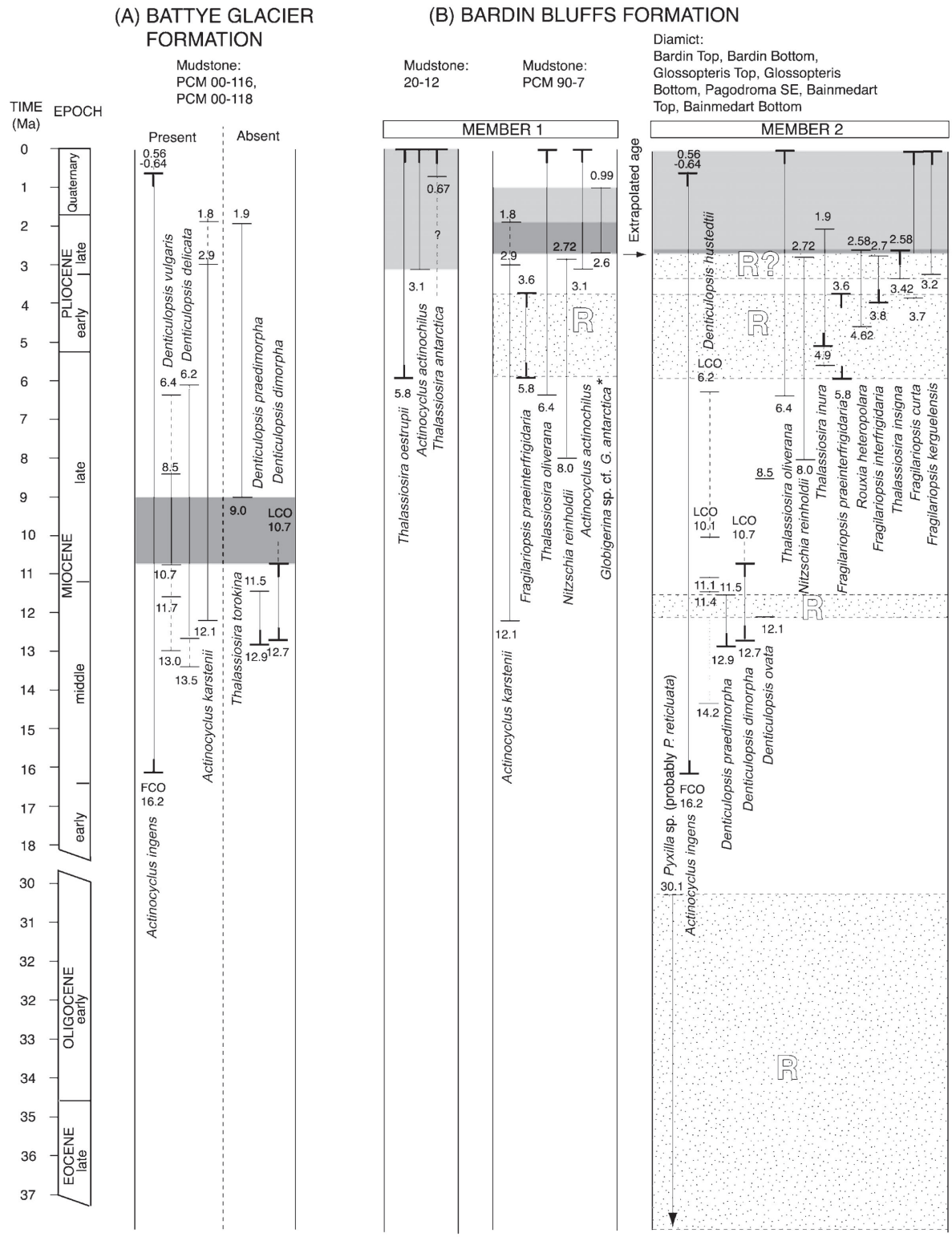

Figure 8. Age ranges inferred from diatom biostratigraphy (samples indicated) of the Battye Glacier and Bardin Bluffs Formations. (a) Battye Glacier Formation biostratigraphic interpretation is depicted by dark-grey hachure that constrains the age based upon "present" and "absent" diatoms. The diatom abundance in the Battye Glacier Formation is comparable to that of open-marine sediments, where the absence of diatom taxa is commonly used to help constrain age. (b) Bardin Bluffs Formation biostratigraphic interpretations for Member 1 and Member 2 are illustrated separately. Dark-grey hachure indicates the most constrained age interpretation from the diatoms present. Light-grey hachure indicates broader age ranges from other reliable diatom data. Stippled areas and the symbol "R" indicates the time range of source areas from which non-*in situ* diatoms have been derived by glacial reworking. The symbol "R?" in Member 2 indicates uncertainty of reworking because *T. insigna* has a very small range overlap of 0.02 million years with the Member 1 basal datum extrapolation (i.e. G. sp. cf. *G. antarctica** foraminiferal datum in McKelvey *et al*. 2001).

Table 2. Biostratigraphic data used in the present study.

Datum	Taxon	Revised age (Ma)[b]	Source(s)	Other reported ages/notes
Zonal markers				
LCO	*Actinocyclus ingens*	0.56–0.64	ZG	B: 0.40–0.55[a]/ RB: 0.3–2.0[b]/ WI: 0.65[b]/ ZG: 0.38[b] (LO) / C, G, HM, GB: 0.66[b] (LCO)
LO	*Thalassiosira insigna*	2.6	C / GB	G: 2.1–2.5[a]/ F: 1.9–2.2[a]/ B: 2.4–2.45[a]/ RB: 1.8–4.6[b]/ WI: 2.54–2.6[b]/ ZG: 2.55–2.66[b]
FO	*Fragilariopsis interfrigidaria*	3.8	G / B / HM / ZG	C: 4.0[a]/ RB: 3.3–4.0[b]/ WI: 2.67–3.9[b]
FCO	*Thalassiosira inura*	4.9	G	B: 4.7–4.8[a]/ RB: 4.5–9.0[b] WI: 5.56[b](FO) / CG: 4.89[b](FO) / ZG: ~4.9[b]
FO	*Thalassiosira oestrupii*	6.2	WI	RB: 4.3–5.1[b]/ B:5.6–5.8[b]
FO	*Thalassiosira torokina*	9.0	HM	C: ~6.0[a]/ G: ~7.7[a]/ B: 7.7[a]/ RB: 8.5–10.0[b]
LCO	*Denticulopsis dimorpha*	10.7	HM	G: 9.8–9.9[a]/ B: 9.9[a]/ RB: 10.2–12.9[b]/ YA: 9.2[b] (LO)
FO	*Denticulopsis dimorpha*	12.7	CG	G: 12.4[a]/ RB: 11.1–13.0[b]/ B, HM: 12.2[b]
FO	*Denticulopsis praedimorpha*	12.9	CG	B: 12.0–12.5[a]/ HM: 12.8[a]/ RB: 12.5–13.4[b]/ /G: 12.82[b]
FO	*Denticulopsis simonsenii*	14.18–14.3	CG	B: 14.0[a] (FCO) / RB: 14.0–14.6[b]/ YA: 14.5–14.6[b] (Northern Hemisphere)
FO	*Actinocyclus ingens* var. *nodus*	14.5	HM	G: ~14.9[a]/ B: 15.0[a]/ RB: 13.1–15.9[b]/ CG: 14.178–14.8[b]
FCO	*Actinocyclus ingens*	16.2	B	G: 15.2[a]/ HM: 15.7[a]/ RB: 15.9–17.5[b]
Secondary data				
FO	*Thalassiosira antarctica*	<0.67	S / B1+	–
LO	*Globigerina* sp. cf. *G. antarctica*[c]	0.99	M	–
LO	*Proboscia barboi*	1.7	F / C / B	HM: 3.1[a] (local extinction) / RB: 1.6–4.2[b]/ ZG: 1.82–1.85[b]
LO	*Thalassiosira inura*	1.9	HM / W	G: ~1.7[a]/ RB: 2.0–3.1[b]/ WI: 1.97[b]
FO	*Globigerina* sp. cf. *G. antarctica* #	2.6	M	–
LO	*Rouxia heteropolara*	2.58	G	RB: 2.2[b]
LO	*Fragilariopsis interfrigidaria*	2.7	HM	C: 2.8[a]/ G: 2.1–2.5[a]/ B: 1.9–2.0[a]/ RB: 1.8–3.3[b]/ ZG: 2.58–2.96[b]
FO	*Actinocyclus actinochilus*	3.1	HM	RB: 2.2–3.2[b]
FO	*Fragilariopsis kerguelensis*	3.2	HM	C: 2.6[a]/ B: 1.9–2.0[a]/ RB: 1.2–3.2[b]/ ZG: 2.04–2.34[b]
FO	*Thalassiosira insigna*	3.42	ZG	RB: 2.7–3.3[b]/ HM: 3.4[b]
LO	*Nitzschia reinholdii*	2.72	ZG	RB: 2.5–4.6[b]/ HM 3.4[b]
FO	*Fragilariopsis curta*	3.7	HM	–
LO	*Fragilariopsis praeinterfrigidaria*	3.6	WH	HM: 3.7[b]/ C: 2.8[a]/ G: 3.6[a]/ RB: 2.1–4.6[b]
FO	*Rouxia heteropolara*	4.62	G / HM	B: 3.8[a]/ RB: 4.0–6.8[b]
FO	*Fragilariopsis praeinterfrigidaria*	5.8	WI	C: 4.3[a]/ B: 4.3–4.6[a]/ RB: 4.5–5.7[b]/ G: 4.9[b]
LO	*Denticulopsis simonsenii*	~4.9	CG	C: 4.4[a] (LO) / B: 6.3[a] (LCO) / G: 4.5[a] (LO) / G: 7.3[a] (LCO) / RB: 4.2–5.4[b] (LO) / B2+: 9.0[b] (LO)
LO	*Denticulopsis delicata*	6.2	BW	–
FO	*Thalassiosira oliverana*	6.4	HM	–
FO	*Nitzschia reinholdii*	8.0	B	HM: 6.4[b]
LO	*Denticulopsis ovata*	~9.0	HM	CG: *4.93*[b]
LCO	*Denticulopsis hustedtii*	10.1	YA	HM: 6.2[b] (when grouped with *D. simonsenii* and *D. vulgaris*)
FO	*Denticulopsis vulgaris*	10.7–11.7	B2+	YA: ~13.0[b] (Northwest Pacific datum)
FO	*Denticulopsis hustedtii*	11.1–11.4	YA	HM: 14.2[b] (when grouped with *D simonsenii* and *D. vulgaris*)
LO	*Denticulopsis praedimorpha*	11.5	B / HM	C: 10.5[a]/ G: 10.4[a]/ RB: 10.9–12.1[b]
FO	*Denticulopsis ovata*	12.11	CG	HM: 11.7[b]
FO	*Actinocyclus karstenii*	12.1	HM	–
LO	*Actinocyclus ingens* var. *nodus*	12.5	G / HM	B: 12.0–12.5[a]/ RB: 9.3–14.6[b]
FO	*Denticulopsis delicata*	12.5–13.5	BW	–
FO	*Proboscia barboi*	12.7	HM	RB: 11.4–11.7[b]
LO	*Stephanopyxis splendidus*	~33	HB	–
LO	*Pyxilla reticulata*	30.1	S	–
LO	*Stephanopyxis grunowii*	~31.3–32	GC	–
FO	*Stephanopyxis splendidus*	~35	HB	GC: ~34[b]

C, Ciesielski (1983); G, Gersonde & Burckle (1990); F, Fenner (1991); B, Baldauf & Barron (1991); HM, Harwood & Maruyama (1992); WH, Winter & Harwood (1997); WI, Winter & Iwai (2002); YA, Yanagisawa & Akiba (1998); RB, Ramsay & Baldauf (1999); S, Scherer 1991; B1+, Bohaty *et al.* (1998); B2+, Bohaty *et al.* (2003); CG, Censarek & Gersonde (2002); ZG, Zielinski & Gersonde (2002) data south of Subantarctic Front; M, McKelvey *et al.* 2001; HB, Harwood & Bohaty (2001); GC, Gombos & Ciesielski (1983); BW, S. M. Bohaty & J. M. Whitehead (unpubl. data); S+, Scherer *et al.* (2000)

a. Berggren *et al.* (1985); b. Berggren *et al.* (1995) /Cande & Kent (1995); c. Foraminiferal data (McKelvey *et al.* 2001)

FO, First Occurrence; FCO, First Common Occurrence; LO, Last Occurrence; LCO, Last Common Occurrence.

Data in italics are considered by the original authors to be of low reliability.

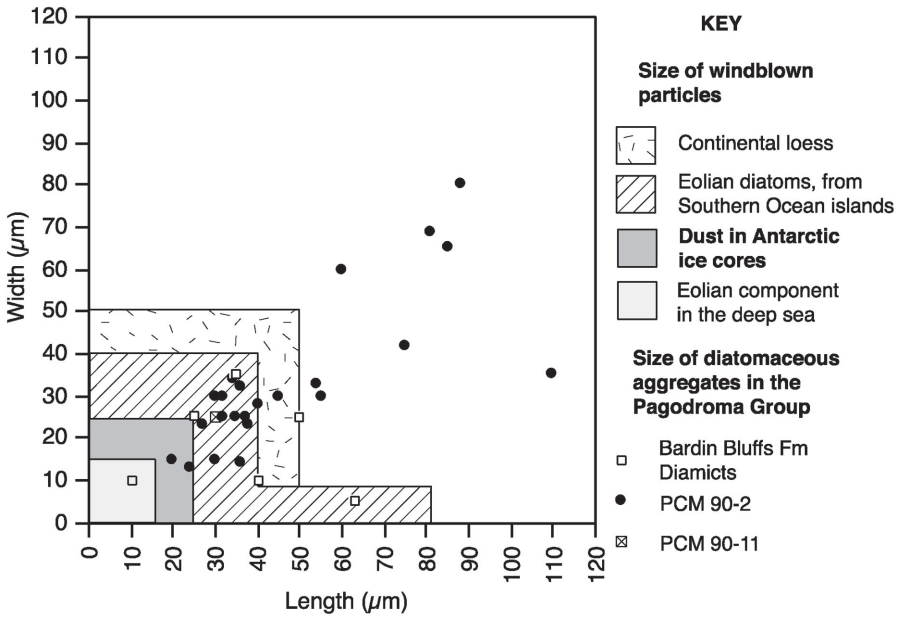

Figure 9. Diatomaceous clasts or aggregates are of similar particle size to aeolian-transported diatoms sampled from Southern Ocean islands (Chalmers *et al*. 1996) and continental loess. All three groups exceed the particle size of aeolian dust in Antarctic ice cores. However, numerous diatomaceous clasts recovered from PCM 90-2 are considerably larger than any of the four categories illustrated (figure modified from Harwood & Webb 1998).

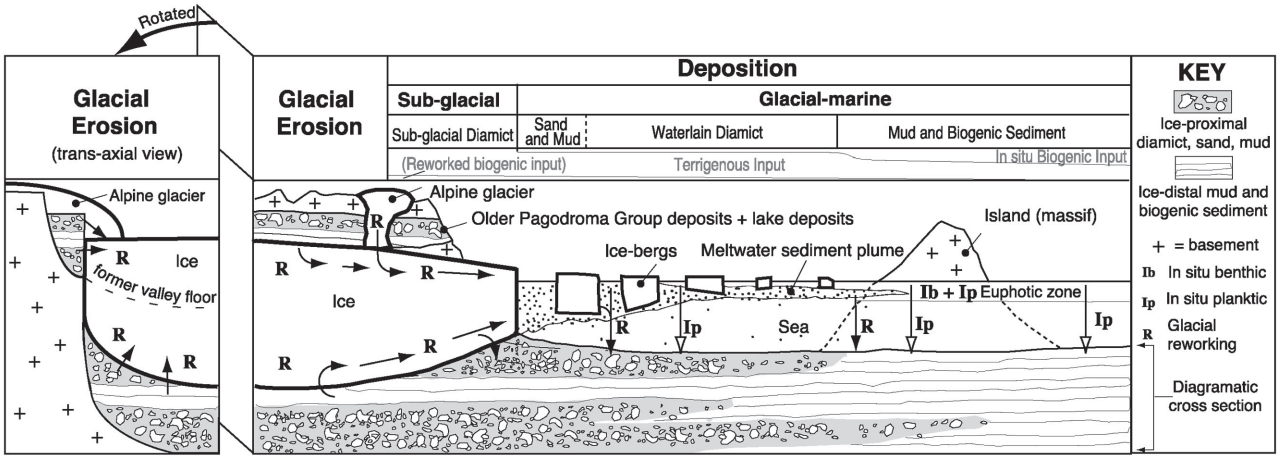

Figure 10. Pagodroma Group erosional and depositional scenario, as proposed by Hambrey and McKelvey (2000a, b), redrawn to incorporate microfossil emplacement by glacial reworking and *in situ* marine deposition. Possible glacial reworking pathways, depicted by "R," include marine sediment eroded from beneath the Lambert Glacier, and similarly eroded by alpine and tributary glaciers. Reworked microfossils are deposited into subglacial diamict, and beyond the ice terminus reworked microfossils are deposited from meltwater plumes and from icebergs into sand, mud and water-lain diamict. Some *in situ* microfossil assemblages also contain older reworked taxa. *In situ* planktic and benthic marine microfossil deposition occurs in the marine environment although relatively biogenic-rich sediments accumulate only in ice-distal settings. The island illustrated may represent the Amery Oasis, and other massifs of the Prince Charles Mountains, during reduced glacial conditions.

Ecological differences between the diatom assemblages in samples 20-12, PCM 98-3Aa-026 and PCM 90-7 suggest a considerable sea-level rise during deposition of Member 1. Samples 20-12 and PCM 98-3Aa-026 contain many shallow marine benthic diatoms, yet sample PCM 90-7 consists almost exclusively of planktic taxa (Table 1). The low abundance of benthic diatoms in the latter sample suggests deposition beneath euphotic depth. The foraminiferal assemblage in PCM 90-7 similarly reflects a deep-water environment (McKelvey *et al*. 2001). This relative transgression is further supported by the presence of a (subaerial) palaeosol on the unconformity surface beneath Member 1 at Bardin Bluffs (Whitehead & McKelvey 2001).

Diatoms from Member 1 mudstone at the "Hiatella location" sample (PCM 90-2: Figure 3d; Table 1) consist largely of extant planktic species, with the exception of extinct planktic taxa *A. ingens* (last occurrence 0.64–0.56 Ma) and *R. isopolica*. The presence of *Thalassiosira oliverana* (O'Meara) Sournia (first occurrence 6.4 Ma) indicates deposition after 6.4 Ma. However, the absence of *A. actinochilus* prevents a more precise comparison with the two mudstones at Bardin Bluffs. Many diatoms in sample PCM 90-2 occur in diatomaceous sediment clasts that are too large to be aeolian contaminants (Figure 9), suggesting that they are reworked glacially from an older marine sediment source.

In Member 2 diamicts of the Bardin Bluffs Formation the presence of *F. kerguelensis* (first occurrence 3.2 Ma) in samples from "Bardin Bottom," "Glossopteris Top," "Glossopteris Bottom," "Pagodroma SE," and "Bainmedart Bottom" (Figure 3b), indicates deposition <3.2 Ma. Their stratigraphic

Table 3. Criteria for assessing diatom emplacement within the Pagodroma Group.

Formations	Bardin Bluffs											Battye Glacier		
Sample Location	1	1	5	5	3	4	4	2	1	1	1	6	6	6
Sample Name	Bardin	Bardin	Gloss	Gloss	Pago	Bain	Bain	PCM	PCM	PCM	PCM 98	PCM	PCM	PCM
Sample Position/Number	top	bottom	top	bottom	SE	top	bottom	90-2	90-3	90-7	3Aa-26	90-8	90-10A	90-10B
Lithology	Dm	Dm	Dm	Dm	Dm	Dm	Dm	Silt.	Dm	Silt.	Silt.	Dm	Dm	Dm
Diatom abundance	3	4	4	3	4	3	3	4	0	5	6	1	0	1
Raw or concentrated slides	conc.	conc.	conc.	conc.	conc.	conc.	conc.	conc.	conc.	conc.	raw	conc.	conc.	conc.
Biogenic silica (% opal)	-	-	-	-	-	-	-	2%	-	1%	2%	-	-	-
Airborne Contamination														
From aeolian deposition														
Predominantly fresh-water diatoms	r	r	r	r	r	r	r	-	-	r?	-	-	-	-
Predominantly benthic diatoms	r	-	r	r	r	-	r?	-	-	r	X	-	-	-
From meteorite impact fallout														
Predominantly planktic with mixed age range (*ca* 50–2.15 Ma)	-	-	-	-	X?	-	-	-	-	-	-	-	-	-
Supporting evidence														
Diatomaceous aggregates	-	X	X	X	X	-	X	X	-	-	-	-	-	-
Glacial Reworking														
From marine strata														
Marine Southern Ocean and Antarctic species	X	X	X	X	X	X	X	X	-	X	X	X	-	X
Supporting evidence														
Diatomaceous aggregates	-	X	X	X	X	-	X	X	-	-	-	-	-	-
Diatoms biostratigraphically mixed (different ages together)	X	-	X	X	X	-	X	-	-	X	-	-	-	-
From lake strata														
Freshwater species	r	r	r	r	r	r	r	-	-	r?	-	-	-	-
Supporting evidence														
Freshwater diatomaceous aggregate	-	-	-	-	-	-	X	-	-	-	-	-	-	-
***In situ* Marine**														
Marine Southern Ocean and Antarctic species	X	X	X	X	X	X	X	X	-	X	X	X	-	X
Supporting evidence														
In situ molluscs	-	-	-	-	-	-	-	X	-	X	-	-	-	-
Diatoms relatively abundant[a]	-	-	-	-	-	-	-	-	-	-	X	-	-	-
Diatoms biostratigraphically unmixed (coherent stratigraphic range)	-	X	-	-	-	X	-	X	-	-	X	X	-	X

a. Diatoms obviously visible in raw samples (approximately 2–12% opal)
X, occurrence in this sample
X, presence of supporting evidence
r, rare in this sample
Other abbreviations are the same as those in Table 1.
This table evolved from a similar table conceptualized by Harwood and Webb (1998).

position above Member 1 at Bardin Bluffs further constrains the age to <2.6 Ma.

Several of the Bardin Bluffs Formation diamicts contain diatoms with considerably disparate age ranges (Figure 8). These data suggest glacial reworking. Thus the Eocene–Oligocene *P. reticulata* may have originated from a source similar to that of the *Pyxilla* sp. found in the Mt Johnston Formation. Reworked Miocene marine diatoms in the diamicts include *D. dimorpha* and *D. praedimorpha*, which lived between 12.9 and *ca* 10.7 Ma. These species have not been recovered from the Miocene Fisher Bench and Battye Glacier Formations, and so their presence in the younger Bardin Bluffs Formation suggests an earlier phase of Miocene marine deposition in the Lambert Graben. As in the Member 1 mudstones (see above) *F. praeinterfrigidaria* in the diamicts records marine deposition in the Lambert Graben at some time between 5.8 and 3.6 Ma. Similarly the presence of *T. insigna* in Member 2 may record Pliocene deposition between 3.4

	Fisher Bench						Mt Johnston						Previous studies			
													Bardin	Battye		Fisher
6	9	9	9	9	8	7	10	10	10	10	10	10	1	11	11	9
AM	PCM	PCM	PCM	AM	AM	AM	PCM	PCM	AM	AM	AM	AM		PCM	PCM	
028	90-6	90-11	90-13	015	017	026	90-4	90-5	002	003	006	014	20-12	00-116	00-118	36721-4
Dm	Silt.	Dm	Dm	Silt.	Dm	Dm	Dm	Dm	Dm	Dm	Dm	Dm	Silt.	Silt.	Silt.	Silt.
0	2	4	0	6	4	1	2	2	0	1	2	2	6	6	6	5
conc.	conc.	conc.	conc.	raw	conc.	conc.	conc.	conc.	conc.	conc.	conc.	conc.	raw	raw	raw	conc.
-	1%	1%	-	~2%	-	1%	-	-	-	-	-	-	-	7%	12%	-
-	-	r	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	X	X
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-
X	X	X	-	X	X	X	X	X	-	X	X	X	X	X	X	X
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	?	-	-	-	-	-	-	-	-	-	-	-	-
-	-	r	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
X	X	X	-	X	X	X	X	X	-	X	X	X	X	X	X	X
-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	-
-	-	-	-	X	-	-	-	-	-	-	-	-	X	X	X	X
X	X	X	-	?	X	X	X	X	-	X	X	X	X	X	X	X

and 2.6 Ma. Alternatively, because *T. insigna* has a 0.02 million year overlap with the youngest age assigned to Member 1 of the Bardin Bluffs Formation (from G. sp. cf. *G. antarctica*, first occurrence 2.6 Ma), its presence could infer a restricted *in situ* formation age between 2.6 and 2.58 Ma. However, this interpretation is probably beyond the resolution of the biostratigraphic dating method.

The freshwater planktic diatoms *Stephanodiscus* sp., *Cyclotella* sp. and *T. fenestrata* in the Bardin Bluffs Formation Member 2 diamicts ("Bardin Top," "Glossopteris Top," "Pagodroma SE," and "Bainmedart Bottom" samples: Figure 3), indicate a post-Late Miocene age for former lake sediments (Bradbury & Krebs 1995) in the Lambert Graben catchment.

Conclusions

Diatom-bearing marine deposits of the Pagodroma Group formed during periods of reduced glacial extent when marine waters penetrated southwards into the Lambert Graben. The two primary modes of diatom emplacement into the Pagodroma Group are (i) *in situ* marine deposition and (ii) glacial reworking of older microfossil-bearing marine and lacustrine strata, as illustrated in Figure 10. *In situ* marine deposition is demonstrated by the relative abundance of diatoms in mudstone sequences bounded by diatom-poor diamicts. Because these mudstones contain few dropstones, we consider them to be the facies most distal from the fjordal ice fronts (Hambrey & McKelvey 2000b) of

the ancestral Lambert Glacier – Amery Ice Shelf drainage system.

The *in situ* deposition of diatoms is further demonstrated (in the Battye Glacier Formation) by the close association of microfossil-bearing mudstones with strata containing fossil molluscs preserved in growth positions. The emplacement of diatoms by glacial reworking is indicated by biostratigraphic age mixing (Figures 7, 8) and by the presence of some diatomaceous clasts that are too large to be aeolian contaminants (Figure 9). The relative insignificance of any aeolian contribution is highlighted by the fact that Pagodroma Group diatom assemblages (with few exceptions) are predominantly of planktic marine taxa. Freshwater taxa are rare. This contrasts with the aeolian diatom contribution in Antarctic ice cores (of South American provenance), which consists predominantly of marine benthic and non-marine species. Airborne diatom emplacement from the Eltanin asteroid impact ejecta is also unlikely. The Eltanin impact reworked Southern Ocean sediment spanning 50–2.15 Ma, and the resulting marine ejecta would be a biostratigraphically mixed assemblage. Those Pagodroma Group assemblages that are biostratigraphically mixed span only a small portion of that 50–2.15 Ma range.

Biostratigraphic interpretation of the Pagodroma Group suggests that at least six episodes of marine deposition occurred in the Lambert Graben >250 km south of the modern Amery Ice Shelf edge (Figure 11). Planktic marine diatoms in diamict of the Mt Johnston formation indicate an Early Oligocene age of between *ca* 35 and 33 Ma, but it is unclear if these fossils are *in situ* or glacially reworked. However, the lack of Miocene fossils and the formation's clearly older (field) relationship to the nearby Fisher Bench Formation (McKelvey *et al*. 2001) indicates that this formation predates the Middle to Late Miocene (>12.1 Ma). Direct evidence of two other episodes comes from the interpretation that *in situ* diatoms occur in mudstones of (i) the Battye Glacier and Fisher Bench Formations and (ii) the Bardin Bluffs Formation. The Battye Glacier and Fisher Bench Formations are broadly correlative with constrained ages between 10.7 and 9.0 Ma, and 10.7 (or 12.1) and 8.5 Ma, respectively. Foraminifers and diatoms in mudstone from the Bardin Bluffs

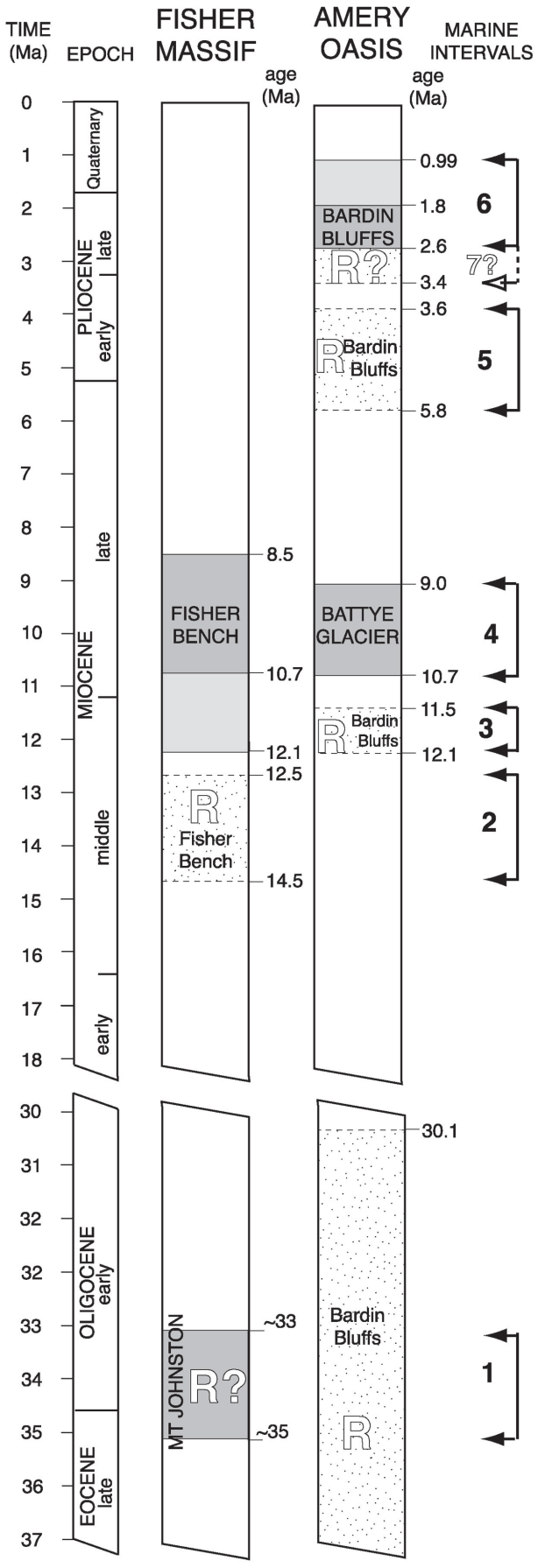

Figure 11. Summary of the diatom biostratigraphic interpretation of the Pagodroma Group. At least six marine intervals in the Lambert Graben are evident from *in situ* and glacially reworked diatoms from Fisher Massif and the Amery Oasis. Symbols and shading as in Figures 4, 5. Marine interval 1 is identified from diatoms (either *in situ* or glacially reworked) in the Mt Johnston Formation. The taxa fall within the age range of the oldest reworked fossils in the Bardin Bluffs Formation. Interval 2 is evident from reworked diatoms in the Fisher Bench Formation. Interval 3 is identified from reworked diatoms in the Bardin Bluffs Formation. Interval 4 is evident from *in situ* diatoms in the similarly aged Fisher Bench and Battye Glacier formations. (The age of the Battye Glacier Formation is also constrained by the conspicuous absence of some diatoms.) Interval 5 is identified from reworked diatoms in the Bardin Bluffs Formation. Interval 6 is evident from *in situ* microfossils in the Bardin Bluffs Formation. In theory it is possible to yet further constrain the age of the Bardin Bluffs Formation to 2.6–2.58 Ma. Alternatively, a seventh interval of marine sedimentation, slightly older than the Bardin Bluffs Formation, can be contemplated.

Formation indicate an age between 2.6 and 0.99 Ma, which may (possibly) be constrained further to 2.6–1.8 Ma. Indirect evidence for four other episodes of marine deposition comes from the identification of glacially reworked diatoms in the Bardin Bluffs Formation, and the Fisher Bench Formation, derived from 14.5 to 12.5 Ma, 12.1–11.5, 5.8–3.6 Ma and, perhaps, 3.42–2.58 Ma strata (Figure 11).

It is to be emphasised, given the known rates of modern east Greenland fjordal sedimentation (Dowdeswell *et al.* 1994), that the episodes of marine sedimentation recorded by the formations did not persist throughout the time intervals defined by their diatom biostratigraphies. The individual Pagodroma Group formations in all probability represent time intervals in the order of only hundreds or thousands of years. Although six depositional episodes are identified, the 40 000 year and 100 000 year cyclicity established for such events elsewhere in Antarctica (Naish *et al*. 2001) suggest that over the 35 Ma timespan indicated by the diatom biostratigraphy, the occurrence of some hundreds of such events is to be contemplated.

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Supplementary Papers (on following pages)

Appendix 1: Siliceous microfossil taxonomy.

Appendix 2: Size and preservation data from select Pagodroma Groups samples.

Diatom biostratigraphy of the Cenozoic glaciomarine Pagodroma Group, northern Prince Charles Mountains, East Antarctica*

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SUPPLEMENTARY PAPERS

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* Appendices 1 and 2 [indicated by an asterisk (*) in the text and listed at the end of the paper] are Supplementary Papers; copies may be obtained from the Geological Society of Australia's website (www.gsa.org.au) or from the National Library of Australia's Pandora archive (http://nla.gov.au/nla.arc-25194).

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Appendix 1: Siliceous microfossil taxonomy

Appendix 2: Size and preservation data from select Pagodroma Groups samples.

APPENDIX 1: SILICEOUS MICROFOSSIL TAXONOMY

Taxa preceded by the symbol * have only been recorded in previous Pagodroma Group studies.

Bacillariophyceae

Achnanthes brevipes Agardh 1824; Roberts and McMinn 1999, p. 15, pl. 1, figs. 3-4; Harwood *et al.* 2000, p. 459, figs 9i-j (as *Achnanthes charcotii*).

Actinocyclus actinochilus (Ehrenberg) Simonsen 1982; Harwood and Maruyama 1992, p. 699, pl. 12, fig. 11; (Figure 6.1).

Actinocyclus ingens Rattray 1890; Harwood and Maruyama 1992, p. 700, pl. 8, fig. 10; pl. 11, fig. 4, 6; pl. 12, fig. 8; (Figure 6.2).

Actinocyclus ingens* var. *nodus Baldauf in Baldauf and Barron 1980; Baldauf and Barron 1980, p. 104, pl. 1, fig. 1-9; (Figures 6.3-4).

Actinocyclus* aff. *ingens Rattray 1891; Schrader 1973, p. 663, pl. 11, fig. 6,7.

Notes: This diatom is thought to be more common in the Miocene (Schrader 1973).

Actinocyclus karstenii Van Heurck 1909; Harwood and Maruyama 1992, p. 700, pl. 13, fig. 1, 2, 6-6, 10, 11, 13; (Figure 6.6).

Actinocyclus octonarius* var. *asteriscus Barron 1975; Harwood *et al.* 2000, p. 459, pl. 7, fig l.

Actinoptycus senarius Ehrenberg 1838; Gombos 1976, p. 655, pl. 26, fig. 1-3; (Figure 6.25).

***Actinoptycus* sp. A**; (Figure 6.24).

***Actinoptycus* spp.** Ehrenberg 1843.

***Amphora* sp. A** of Roberts and McMinn 1999, p. 16, pl. 1, figs. 6-7.

***Amphora* spp.** (Ehrenberg) Kützing 1844.

***Anaulus* sp.** Ehrenberg 1844.

***Astromphalus* spp.** Ehrenberg 1844.

***Aulacoseira* sp.**; (Figure 6.18-19).

Azpeitia tabularis (Grunow) Fryxell and Sims 1986; Akiba 1982, p. 42, pl. 2, fig. 6a, 9.

***Caloneis* sp. A.**

Chaetoceros lorenzianus Grunow (Dicladia pylea Hanna and Grant); Harwood and Maruyama 1992, pl. 18, fig. 11.

****Chaetoceros mitra*** (Bailey) Cleve.

****Chaetoceros subsecundus*** (Grunow) Hustedt.

***Chaetoceros* sp. A** Harwood and Maruyama 1992, pl.19, figs. 9-10.

***Chaetoceros* spp.** Ehrenberg 1844.

Cocconeis costata Gregory 1855; Roberts and McMinn 1999, p. 19, pl. 2, fig. 5.

Cocconeis fasciolata (Ehrenberg) Brown 1920; Roberts and McMinn 1999, p. 20, pl. 2, fig. 4.

Cocconeis pinnata Gregory *ex* Greville 1859; Roberts and McMinn 1999, p. 20, pl. 2, fig. 6.

***Cocconeis* sp. A** of Roberts and McMinn 1999, p. 21, pl. 2, figs. 7-10.

Coscinodiscus oculoides Karsten 1905

Coscinodiscus oculus-iridus Ehrenberg 1839; Harwood 1989, p. 78, pl. 1, fig. 1.

Coscinodiscus radiatus Ehrenberg 1939; Harwood 1989, p. 78, pl. 1, fig. 5

Coscinodiscus marginatus Ehrenberg, Hustedt 1930; Barron 1981, p. 118, pl. 1, fig. 2; (Figure 6.8).

***Coscinodiscus* sp. A**; (Figure 6.20).

***Coscinodiscus* spp.** Ehrenberg 1838.

***Cyclotella* spp.** Kützing 1834.

Dactyliosolen antarcticus Castracane 1886.

Denticulopsis delicata Yanagisawa and Akiba 1990, pl 7, figs. 1-4; (Figure 5.8).

Denticulopsis dimorpha (Schrader) Simonsen 1979; Yanagisawa and Akiba 1990, p. 254-255, pl. 4, figs. 42-49; pl. 7, figs. 14-16; (Figures 5.2-3).

Denticulopsis hustedtii (Simonsen and Kanaya) Simonsen 1979; Yanagisawa and Akiba 1990, p. 246-248, pl. 3, figs. 15-16; pl. 11, figs. 11-13; (Figure 5.1).

Denticulopsis ovata (Schrader) Yanagisawa and Akiba 1990; Harwood and Maruyama 1992, p. 702-703, pl. 6, figs. 1-4; pl. 7, figs. 1-4, 6-9, 11-13; pl. 9, figs. 1-4,10-14; pl. 10, fig. 7 (as *Denticulopsis meridonalis* Maruyama in Harwood and Maruyama 1992); (Figure 5.5).

Denticulopsis praedimorpha Barron *ex* Akiba 1982; (Figure 5.6); Harwood and Maruyama 1992, p. 703, pl. 6., figs. 8-10, 12, 14-17.

Denticulopsis simonsenii Yanagisawa and Akiba 1990, p. 242-243, pl. 3, figs. 1-3; pl. 11, figs. 1-5; (Figure 5.7).

Notes: *Denticulopsis simonsenii* was separated from *Denticulopsis vulgaris* using the species concepts illustrated and described by Yanagisawa and Akiba (1990). *Denticulopsis simonsenii* is characterised by more and 2 full striae of aerolae between the psuedosepta, whilst *D. vulgaris* has incomplete rows of areolation on either side (and near) each psuedosepta.

Denticulopsis vulgaris (Okuno) Yanagisawa and Akiba 1990, p. 243-244, pl. 3, figs. 4-8; pl. 11, figs. 6-10.

Notes: See notes under *Denticulopsis simonsenii*.

Denticulopsis spp. (Simonsen) Akiba and Yanagisawa 1990.

***Diploneis* sp. A.**

Diploneis frickei (Van Heurck) Heiden and Kolbe 1958; Harwood *et al.* 2000, p. 459, pl. 9, fig m.

****Diploneis oculata*** (Brébisson) Cleve 1894-1895.

Diploneis subovalis Cleve 1894; Harwood *et al.* 2000, p. 459, pl. 9, fig. l.

****Diploneis smithii*** (Brébisson) Cleve 1894-1895.

Diploneis bomboides (Schmidt) Cleve 1894-1895; Roberts and McMinn 1999, p. 21, pl. 3, fig 1, (as *Diploneis splendidus* (Gregory) Cleve 1894-1895).

Eucampia antarctica (Castracane) Mangin 1914; (Figure 6.7).

****Eunotia* sp.** Ehrenberg 1837.

***Fragilaria* spp.** Lyngbye 1819.

Fragilariopsis curta (Van Heurck) Hasle 1958; Harwood and Maruyama 1992, p. 704, pl. 17, figs. 1-4 (as *Nitzschia curta* (Van Heurck) Hasle 1972).

Fragilariopsis interfrigidaria (McCollum) Gersonde and Bárcena 1998; Baldauf and Barron 1991, p. 589, pl. 7, fig. 12 (as *Nitzschia interfrigidaria* McCollum 1975); (Figure 5.9).

Fragilariopsis kerguelensis (O'Meara) Hasle 1952; Medlin and Priddle 1990, p. 181, pl. 24.2, fig. 11-18; p. 187, pl. 24.3, fig. 9 (as *Nitzschia kerguelensis* (O'Meara) Hasle 1972); (Figure 5.11; Figure 6.15).

Fragilariopsis praeinterfrigidaria (McCollum) Gersonde and Bárcena 1998; Barron 1985, p. 805, fig. 14, fig. 5,6 (as *Nitzschia praeinterfrigidaria* McCollum 1975); (Figure 5.9).

***Fragilariopsis sublinearis** *(Van Heurck) Heiden 1928.*

Fragilariopsis **spp.** Hustedt 1913.

Gomphonema angustatum **var. A**; (Figure 5.14).

Synonym: *Navicula* sp. in Winter 1995, pl. 7, figs. 2-4.

Gomphonema angustatum **var. B**; (Figure 5.15).

Grammatophora **spp.** Ehrenberg 1840.

Hyalodiscus valens Schmidt 1888; Harwood et al. 2000, p. 459, pl. 8, fig. h.

****Hyalodiscus obsoletus*** Sheshukova.

Hyalodiscus zonulatus Peragallo 1921; Harwood *et al.* 2000, p. 459, pl. 8, fig. l.

****Hyalodiscus*** **sp.** Ehrenberg 1845.

Isthmia **sp.** Agardh 1832.

Melosira **sp.** Agardh 1824.

Notes: possibly recorded as ****Podosira sp.*** by Bardin and Belevich (1985).

****Navicula cryophila*** Manguin 1957.

Navicula directa (Smith) Ralfs in Pritchard 1861; Roberts and McMinn 1999, p. 31, pl. 4, fig. 13.

****Navicula glaciei*** Van Heurck 1909.

Synonym: ****Navicula gelida*** **var.** ***parvula*** Heiden and Kolbe 1928.

Notes: synonym recorded as a separate species in Bardin and Belevich (1985) with an abundance of 1-5 specimens per field-of-view. The *N. glaciei* abundance has been altered to 1-10 to accommodate this.

Navicula retusa Donkin.

Synonym: *Navicula cancellata* var. *retusa* (Brébisson) Cleve.

***Navicula* spp.** Bory 1822.

Nitzschia acicularis (Kützing) Smith 1853.

Nitzschia cholonii Van Heurck?

Nitzschia delicatissima Cleve.

Nitzschia frustulum (Kützing) Grunow.

Nitzschia scabra Cleve.

***Nitzschia* sp. A** as in Harwood 1989.

Nitzschia reinholdii Kanaya *ex* Barron and Bauldauf 1986; Gersonde and Burckle 1990, p. 782 pl. 2, fig. 1; (Figure 5.10).

***Nitzschia* sp**. Hassall 1845.

Odontella weissflogii (Janisch) Grunow.

Paralia sulcata (Ehrenberg) Cleve 1873; Harwood and Maruyama 1992, p. 704, pl. 1, fig. 9

***Paralia* sp.** Heiberg 1863.

Pinnularia quadratea (Schmidt) Cleve 1895; Harwood et al. 2000, p. 460, pl. 10, fig, f.

***Pinnularia* sp. A.**

Porosira antarctica Kozlova 1962.

Notes: possible synonym to *Porosira glacialis* (Grunow) Jørgensen; however, *Porosira antarctica* is considered to be smaller and usually weakly silicified (Priddle and Fryxell 1985).

Porosira pseudodenticulata (Hustedt) Jousé 1962.

Proboscia barboi (Brün) Jordan and Priddle 1991; Harwood and Maruyama, 1992, p. 706, pl. 11, fig. 13.

Pyxilla* sp.** (Pyxilla reticulata*** Grove and Sturt 1887); (Figure 5.3).

Synonym: Fenner 1985 notes that *P. prolongata* Brun and *P. johnsoniana* Forti 1909 are probably synonyms of *P. reticulata.*

Notes: The *Pyxilla* sp. fragments appear to be *P. reticulata* and can be differentiated from other *Pyxilla* spp. (or *Pyrgupyxis* spp.). *Pyxilla reticulata* has finer areolae 3-6 in 10 *µ*m (Fenner 1985), whilst *P. oligocenica* Jousé has coarser areolae: 2-3 in 10 *µ*m (Fenner 1985) and *P. gracilis* Tempère *et* Forti has coarser areolae, 2-3 in 10 *µ*m (Fenner 1985), and a smoother valve surface (Gombos 1987, p. 798, pl. 1, fig. 5; Fourtanier 1991, p. 186, pl. 4, fig. 10). *Pyrgupyxis. eocena* Hendy has a distinctly different shape to *P. reticulata* (Gombos 1976, p. 647, pl. 22, figs 6-7; Harwood and Bohaty 2001, p. 330, pl. 4, fig. 5. *Pyxilla reticulata* is the only species within the *Pyxilla* genus identified from marine strata in Prydz Bay (Barron and Mahood 1993).

Rhabdonema japonica group Tempère and Brün in Brün and Tempère 1889; Harwood *et al.* 2000, p. 460, pl. 9, fig. K; (Figure 5.16).

****Rhabdonema* sp. cf. *R. elegans*** Tempère and Brün.

***Rhabdonema* spp.** Kützing 1844

***Rhaphoneis* spp.** Ehrenberg 1845; (e.g. Figure 5.19).

Rhizosolenia hebetata group Bailey 1856; (Figure 6.17); Koizumi, 1973, p. 833, pl. 5, fig. 35.

Notes: This group consists of *Rhizosolenia* spp. lacking otaria.

Rhizosolenia styliformis group Brightwell 1858; Harwood and Maruyama 1992, p. 705, pl. 18, fig. 20.

Notes: This group consists of *Rhizosolenia* spp. with otaria.

Rouxia heteropolara Gombos 1974; (Figure 5.18); Gersonde and Burckle 1990, p. 782, pl. 5, fig. 2.

Rouxia isopolica Schrader 1976, p. 635-636, pl. 5, figs. 9, 14-15, 20. (Figure 5.17).

Rouxia naviculoides Schrader 1973, p. 710, pl. 5, figs. 27-32.

***Rouxia* spp.** Brün and Heribaud 1893

Stellarima microtrias (Ehrenberg) Hasle and Sims 1986; (Figure 6.9); Harwood 1989, p. 80 pl. 1, fig. 4.

Stellarima stellaris (Roper) Hasle and Sims 1986; (Figure 6.9); Harwood 1989, p. 80, pl. 1, fig. 3.

****Stellarima* spp.** Hasle and Sims 1986.

***Stephanodiscus* spp.** Ehrenberg 1845; (Figure 6.18).

Stephanopyxis grunowii Grove and Sturt 1888; Harwood, 1989, p. 81, pl. 2, fig. 1, 2-4.

Stephanopyxis splendidus (Greville) Harwood 1989; (Figure 6.10); Harwood 1989, p. 81, pl. 2, fig. 1, 2-4.

Stephanopyxis turris (Greville and Arnott) Ralfs, in Pritchard 1861; (Figure 6.11); Harwood, 1989, p. 81, pl. 2, fig. 21-23.

Stictodiscus hardmanius Greville 1865; Harwood 1989, p. 81, pl. 1, fig. 6.

***Syndera* sp.** Ehrenberg 1832.

***Synedropsis* spp.** Hasle *et al.*

Tabellaria fenestrata (Lyngb.) Kützing 1844; Contant and Duthie 1978, p 43 pl. XV figs. 4-7.

***Tabellaria* sp.** Ehrenberg *ex* Kützing 1844.

Thalassionema nitzschioides group Grunow, in Van Heurck; (Figure 5.12).

Thalassionema nitzschioides* var. *parva Heiden 1928; Koizumi and Tanimura 1982, p. 300, pl. 6, fig. 11.

****Thalassiosira antarctica*** Comber 1896.

Thalassiosira gracilis* var. *gracilis (Karsten) Hustedt 1958; (Figure 6.23); Johansen and Fryxell 1985, p. 168-170, fig 58, 59.

Thalassiosira insigna (Jousé) Harwood and Maruyama 1991; Harwood and Maruyama 1992, p. 707, pl. 14, fig. 3-5.

Thalassiosira inura Gersonde 1991; Harwood and Maruyama 1992, p. 707, pl. 5, fig. 14; pl. 14, fig. 12-14, 16.

Thalassiosira nativa Sheshukova-Poretzkaya 1959; Baldauf and Barron 1991, p. 597, pl. 6, fig 5.

Notes: appears like *T. inura*, but differentiated in that the central haline area is smaller in *T. nativa.*

Thalassiosira oliverana (O'Meara) Makarova and Nikolaev 1983; (Figure 6.12); Abbott 1974, p. 319, pl. 2, fig. D-F.

****Thalassiosira oestrupii*** (Ostenfeld) Hasle 1972.

***Thalassiosira* spp.** Cleve 1873.

***Thalassiothrix* sp.** Cleve and Grunow 1880.

Trachyneis aspera (Ehrenberg) Cleve 1984; Roberts and McMinn 1999, p. 44, pl. 7, fig. 9.

****Triceratium oamaruense* var. *sparsipunctatum*** Grove.

Trinacria excavata Heiberg 1863; (Figure 6.22); Harwood 1989, p. 82, pl. 3, fig. 1.

****Trigonium arcticum*** (Brightwell) Cleve 1868.

Gen. et sp. B of Harwood 1986a.

Dinophyceae

Actiniscus pentasteris (Ehrenberg) Ehrenberg 1854.

Dictyochophyceae

***Distephanus* spp.** Stoehr 1880; (Figure 6.16).

Ebriophyceae

Pseudammodochium lingii Bohaty *et* Harwood 2000; (Figure 6.21).

Appendix 2. Size and preservation data from select Pagodroma Groups samples.

Bardin Bluffs Formation

Sample PCM 90-2

Diatomaceous aggregate	length μm	30	45	20	36	55	55	60	30	32	37	27	40	85	75	24	32	110	36	35	34	38	54	88	81															
	width μm	15	30	15	32	30	30	60	30	25	25	23	28	65	42	13	30	35	14	25	34	23	33	80	69															
Thalassiothrix / Thalassionema	length μm	23	20	23	15	10	15	15	20	18	14	16	23	7	7	6	8	25	17	15	14	7	3	20	9	12	16	19	30	17	20	40	9	3						
	width μm	3	3	3	3	4	3	3	3	3	3	2	3	3	3	3	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	5	3	3						
Thalassiothrix / Thalassionema	length μm	6	3	3	6	9	6	16	16	3	16	10	3	15	15	25	6	3	8	8	6	6	6	10	15	10	25	10	10	10	10	25	20	16						
	width μm	3	3	3	3	3	3	3	3	3	3	4	3	3	3	4	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	3	3	3						
Centric fragments	length μm	12	10	4	15																																			
	width μm	4	7	4	6																																			

Glossopteris Top

Diatomaceous clast	length μm	50																																						
	width μm	25																																						

Glossopteris Bottom

Diatomaceous clast	length μm	63	10	25																																				
	width μm	5	10	25																																				

Bardin Bottom

Diatomaceous clast	length μm	35																																						
	width μm	35																																						

Fisher Bench Formation

PCM 90-11

Diatomaceous clast	length μm	30																																						
	width μm	25																																						
Sponge spicule	length μm	110	10	20																																				
	width μm	3	3	10																																				
Thalassiothrix / Thalassionema	length μm	25	25	20	15	10	10	30	5	10	10	20	20	20																										
	width μm	3	3	3	3	3	3	4	3	3	3	3	3	3																										
Centric fragments	length μm	65	3	20	3	12	10	8	3	5	10	5	8	5	6	3	5	10	5	8	5	6	5	15	40	15	20	3	20	8	20	5	20	15	5	20				
	width μm	40	3	10	3	10	8	4	3	5	10	5	5	3	4	3	5	10	5	5	3	4	5	10	20	8	15	3	10	8	5	5	10	12	5	10				
Centric fragments	length μm	15	5	5	15	15	10	20	15	15	20	25	5	5	20	10	3	5	20	7	5	20	20	3	15	10	20	5	3	3	20	15	3	8	3	25				
	width μm	15	5	3	15	15	5	15	5	15	5	10	3	3	15	5	2	5	10	5	5	20	10	3	10	10	10	3	2	3	20	15	3	5	3	25				
Centric fragments	length μm	3	5	30	5	6	3	5	5	20	3	10	10	3	10	5	5	5	10	5	5	10	10	10	20	5	8	5	20	8	40	27	15	15	15	12				
	width μm	3	3	20	5	6	3	3	3	20	3	5	10	5	5	2	5	5	5	5	3	5	5	10	8	3	8	5	10	8	35	10	15	15	8	12				
Centric fragments	length μm	6	40	20	10	6	27	4	20	20	6	27	20	10	20	10	15	15	20	12																				
	width μm	6	35	10	10	6	20	4	15	15	6	20	10	10	10	6	15	10	10	10																				
Intact pennates	length μm	36	47	45	45	40	45	50	40	40	35	40	47	45	47	35	40	45	35	47	47	45																		
	width μm	8	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10																		